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Tesi di Laurea di Primo Livello

Analisi dello stato dell'arte dei sistemi automatici e flessibili di produzione

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SOMMARIO

La tesi si propone di approfondire le tematiche attinenti ai sistemi flessibili di assemblaggio come componenti chiave di una produzione altamente efficiente. A causa di lotti di produzione di dimensioni molto piccole e alla necessità di prodotti personalizzati, è sempre più richiesta maggiore flessibilità e adattabilità nelle mansioni.

Il lavoro risulta così strutturato:

- nel Capitolo 1 forniamo una breve descrizione dei sistemi logistici integrati e flessibili, che siano in grado di realizzare l'integrazione dei flussi fisici e dei flussi informativi per garantire: sia un elevato livello qualitativo dei prodotti e del servizio ai clienti, tramite la riduzione del tempo di risposta all'ordine e il contenimento dei costi di produzione; sia di far fronte con adeguata flessibilità al cambiamento continuo della gamma produttiva, conseguente alla variabilità e alla personalizzazione dei gusti del consumatore;
- nel Capitolo 2 raccogliamo una serie di articoli sullo stato dell'arte sui sistemi di assemblaggio e sulle tecniche di alimentazione flessibile degli ultimi dieci anni. Un ostacolo fondamentale per l'applicazione economica dell'automazione flessibile è l'alimentazione delle parti componenti. Tradizionalmente tale compito viene demandato ai vibroalimentatori i quali hanno un costo elevato e sono dedicati a un singolo componente. Di conseguenza il numero di alimentatori dedicati richiesto nel caso di una elevata varietà di prodotti è pari al numero delle distinte parti che compongono il mix produttivo. Ciò comporta un costo elevato degli investimenti giustificato solo nel caso della produzione di massa. Inoltre metodi di alimentazione dedicati risultano poco flessibili nel caso si utilizzino sistemi di montaggio robotizzati dove si produce una vasta gamma di componenti in piccoli lotti;
- nel Capitolo 3 presentiamo in modo approfondito i lavori di M. Morioka, S. Sakakibara (2010) e J. Krüger, T.K. Lien, A. Verl (2009);
- nel Capitolo 4 concludiamo la tesi esponendo in primo luogo i risultati ottenuti. Successivamente vengono proposti alcuni suggerimenti per i lavori futuri, consapevoli che molto lavoro rimane da fare in merito ai siste-

mi di produzione ed assemblaggio flessibile. Infine vengono tratte alcune conclusioni.

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Capitolo 1

LOGISTICA INTEGRATA E FLESSIBILE

L'OBIETTIVO di questo capitolo è quello di fornire una breve descrizione dei sistemi logistici integrati e flessibili, che siano in grado di realizzare l'integrazione dei flussi fisici e dei flussi informativi per garantire: sia un elevato livello qualitativo dei prodotti e del servizio ai clienti, tramite la riduzione del tempo di risposta all'ordine e il contenimento dei costi di produzione; sia di far fronte con adeguata flessibilità al cambiamento continuo della gamma produttiva, conseguente alla variabilità e alla personalizzazione dei gusti del consumatore (per una trattazione dettagliata dell'argomento Vedere [34]).

1.1 Definizione della funzione logistica

La *logistica* è la disciplina che tratta in maniera organica e sistematica la gestione integrata (Figura 1.1) dell'intero ciclo operativo dell'azienda, industriale o del terziario, attraverso le sue principali funzioni di:

- gestione dei materiali;
- gestione della produzione;
- gestione della distribuzione fisica dei prodotti finiti.

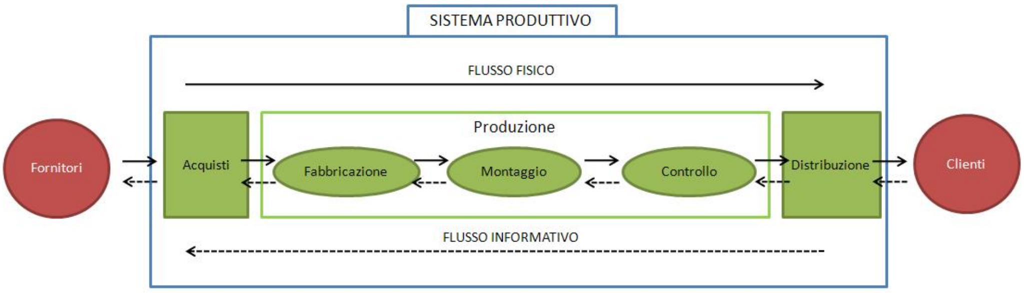

Figura 1.1: Schema della funzione logistica.

Si pone l'obiettivo fondamentale di garantire un elevato livello di servizio ai clienti, fornendo prodotti di alta qualità, con rapidi tempi di risposta e a costi contenuti. Gli strumenti per l'ottenimento di questi obiettivi sono:

① l'integrazione dei flussi fisici e informativi;

② la flessibilità dei mezzi produttivi e logistici.

Al fine di far fronte con rapidità e senza oneri di adattamento al continuo cambiamento della gamma produttiva conseguente alla variabilità del mercato bisogna crescere nell'integrazione fra sistema informativo e sistema produttivo attraverso:

L'integrazione : con una crescita modulare affinché i moduli siano interfacciabili dal punto di vista software, hardware e meccanico;

La flessibilità : deve essere possibile riconfigurare i moduli mantenendo inalterata l'interfaccia con gli altri moduli.

1.2 Flessibilità come risposta alla variabilità

La variabilità del mercato odierno richiede una continua evoluzione ed innovazione dei tipi di prodotto offerti ed una loro sempre più spinta personalizzazione. Per questo bisogna realizzare una produzione flessibile ed elastica attraverso l'automazione flessibile dei sistemi e dei processi produttivi.

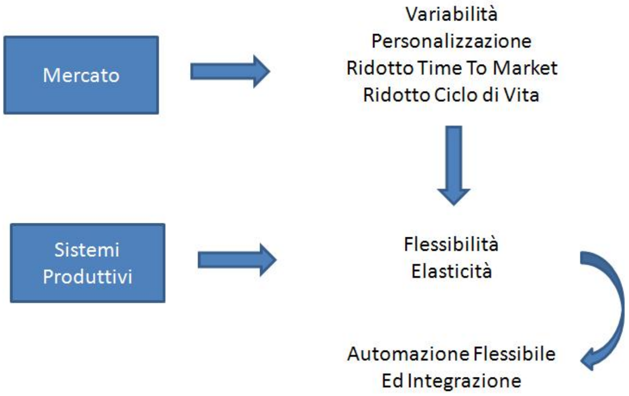

Figura 1.2: Flessibilità/Integrazione come risposta alla variabilità.

Il concetto di fabbrica automatica flessibile si è sviluppato come risposta alla tendenza mondiale verso un tipo di produzione per lotti, tendenza indotta dalla economia concorrenziale o di mercato. Questo ha portato:

- alla ricerca di nuove tecnologie di fabbricazione per la riduzione dei prezzi dei prodotti;

- ad un incremento della varietà dei prodotti al fine di una maggior personalizzazione;
- all'introduzione frequente di nuovi prodotti al fine di ridurne il ciclo di vita;
- alla riduzione dei lotti di produzione.

Con l'inizio del nuovo secolo è iniziata l'era della produzione flessibile (fabbrica moderna), concomitante con il tramonto della produzione di massa (fabbrica tradizionale). La fabbrica moderna si caratterizza per:

① **elasticità del sistema produttivo** per rispondere a variazioni quantitative del mercato;

② **flessibilità del processo produttivo** per rispondere a variazioni qualitative del mercato ovvero possibilità di variare il proprio mix produttivo. Questo si traduce in:

  - flessibilità nelle attrezzature di produzione;
  - flessibilità nel sistema logistico;
  - flessibilità nel sistema di gestione e controllo.

L'automazione integrata e flessibile è quindi lo strumento essenziale della fabbrica moderna attraverso:

- l'automazione del flusso dei materiali e delle attività di produzione;
- l'automazione del controllo di processo.

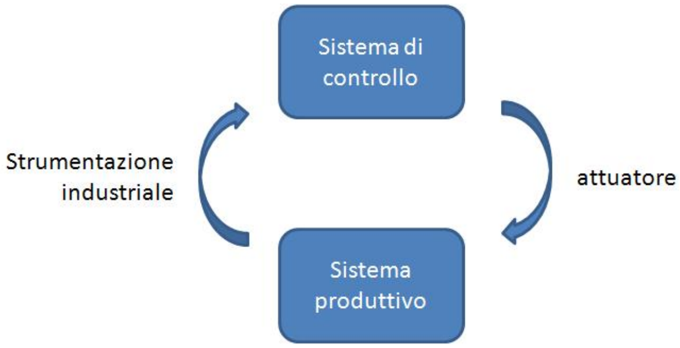

Figura 1.3: Automazione integrata e flessibile.

Le attività di interazione e di elaborazione sono svolte da un programma che utilizza come ingresso delle informazioni ottenute da un sistema di sensori e che produce come uscita una modifica generata mediante un sistema di attuatori.

1.3 Analisi P-Q e tipologie di layout

La disposizione planimetrica o layout delle macchine e delle attrezzature costituenti l'impianto tecnologico principale dipende innanzitutto dal tipo di prodotto (e quindi di processo da eseguire) e dal numero di prodotti da realizzare nell'unità di tempo (o potenzialità produttiva).

La scelta e la tipologia dei mezzi logistici per la movimentazione dei materiali dall'inizio alla fine del processo produttivo dipendono a loro volta, oltre che dalle caratteristiche fisiche e dimensionali delle materie prime, dai materiali in lavorazione e dai prodotti finiti, dalle caratteristiche del layout.

Per procedere allo studio del layout generale di un sistema di produzione è necessario innanzitutto raccogliere informazioni sulla gamma dei prodotti P_k e sulle rispettive potenzialità Q_k (unità/anno) con $k = 1, 2, \ldots, n$. Si realizza un diagramma P-Q (Figura 1.4) in cui i prodotti P_k sono rappresentati sull'asse delle ascisse per potenzialità decrescente.

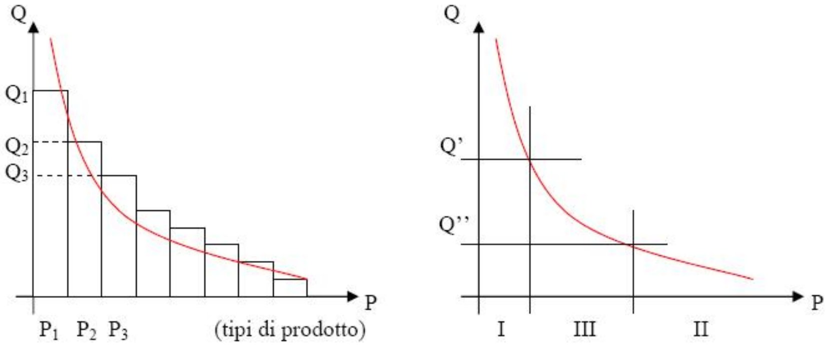

Figura 1.4: Diagramma P-Q.

I prodotti che ricadono nella **zona I** sono eseguiti in grande quantità, quindi favoriscono i metodi di produzione di massa attraverso linee di produzione dedicate. Si ottengono pertanto disposizioni di layout per prodotto nelle quali la collocazione delle macchine e dei mezzi produttivi rispecchia la successione delle operazioni del ciclo tecnologico del prodotto.

I prodotti che ricadono nella **zona II** sono eseguiti in piccole quantità, quindi per questi non è economicamente fattibile la costruzione di linee dedicate a ciascuno di essi. Risultano quindi favoriti i metodi di produzione per reparti di lavorazioni omogenee o a punto fisso, si ottengono in questo caso:

1. *layout per processo*: le lavorazioni vengono eseguite in reparti caratterizzati da lavorazioni omogenee;

2. *layout a posizione fissa*: il prodotto rimane fermo al centro del layout e sono gli operatori ed i mezzi operativi che si muovono intorno ad esso, facendo confluire i componenti e le parti necessarie (tipico per prodotti molto voluminosi o pesanti).

Nelle **zona centrale III** si ha una numerosità intermedia della gamma produttiva con corrispondenti valori intermedi di potenzialità. La risposta tradizionale è la *configurazione mista* del layout ove vengono collocate linee produttive per i pochi prodotti a potenzialità più elevata o addirittura piccole linee che realizzano una parte del processo produttivo comune all'intera gamma, all'interno di un layout per reparti.

La risposta innovativa è quella di ricorrere all'aggregazione di più prodotti simili in famiglie. In questo modo la numerosità della famiglia diventa tale da giustificare una linea dedicata alla famiglia di prodotti con ottenimento del così detto *layout per famiglia di prodotti* (*Group Technology* o tecnologia per famiglie). Necessariamente la linea deve essere flessibile in quanto lavora prodotti simili ma non uguali.

Con riferimento alla Figura 1.4, l'analisi Prodotto - Quantità porta alla individuazione delle seguenti tipologie di layout:

$$\begin{cases} \text{per} & Q > Q' & \textit{layout per prodotto} \\ \text{per} & Q < Q'' & \textit{layout per processo o a posizione fissa} \\ \text{per} & Q'' < Q < Q' & \textit{layout misto o metodologia Group Technology} \end{cases}$$

1.4 Group technology e i sistemi flessibili di fabbricazione

Qualora la produzione sia caratterizzata da grande varietà di prodotto ma piccola numerosità dei lotti, l'organizzazione per reparti è quella che garantisce la massima flessibilità. Per contro si hanno complicazioni nella gestione (soprattutto nel flusso delle parti e delle informazioni) nonché flow time elevati.

1.4.1 La group technology

La **Group Technology**, avvalendosi del progresso tecnologico dei mezzi produttivi, consente di contemperare i vantaggi delle linee dedicate e delle organizzazioni flessibili. Ciò è reso possibile raggruppando prodotti "*simili*" dal punto di vista produttivo e/o progettuale in famiglie. In questo modo si ottengono valori di numerosità dei pezzi della famiglia tali da rendere economicamente valida l'introduzione di una linea (cella flessibile) dedicata alla famiglia stessa.

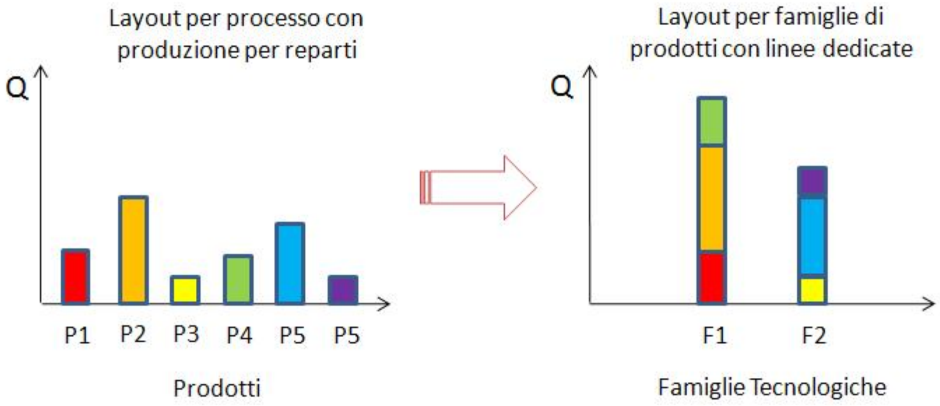

Figura 1.5: Famiglie tecnologiche.

Nel ricercare le similitudini si possono considerare principalmente::

- attributi di progetto (forma geometrica, dimensioni, etc.);
- attributi di fabbricazione (ciclo di produzione, attrezzature necessarie, etc.).

Nella pratica industriale per la generazione delle famiglie sono impiegate diverse metodologie.

Ispezione visuale

É questo il metodo più economico, semplice e rapido. La classificazione delle parti in famiglie è fondata semplicemente sull'osservazione diretta dei prodotti, eventualmente dei loro progetti (qualora non siano ancora in produzione) e/o prototipi. É pertanto un metodo soggettivo e richiede una ottima conoscenza dei processi di fabbricazione e dei prodotti.

Classificazione delle parti

É una metodologia maggiormente oggettiva rispetto alla precedente, consiste nella classificazione dei prodotti e delle loro parti secondo caratteristiche costruttive e/o funzionali. Nella sostanza si sviluppa l'analisi attraverso "check list", che permettono la formalizzazione delle principali caratteristiche di progetto e di produzione, di cui la Tabella 1.1 ne riporta un esempio.

Analisi del flusso produttivo (productive flow analysis - PFA)

É il metodo più dispendioso e di conseguenza più preciso e oggettivo. Consiste nell'analizzare il ciclo di lavorazione piuttosto che il disegno delle parti

Tabella 1.1: Esempio check list attributi di progetto e di produzione.

Attributi di progettazione	Attributi di produzione
Forma esterna fondamentale	Processi principali
Forma interna fondamentale	Operazioni secondarie
Forma prismatica o rotazionale	Sequenza delle operazioni
Rapporto lunghezza/diametro (solidi di rivoluzione)	Macchina utensile
Rapporto d'aspetto (parti prismatiche)	Utensili
Tipo di materiale	Tempo di ciclo
Funzione della parte	Dimensione del lotto
Dimensioni principali	Dimensioni principali
Dimensioni secondarie	Attrezzature richieste
Tolleranze	Tolleranze
Finitura superficiale	Finitura superficiale

stesse al fine di individuare dei gruppi di prodotti realizzabili con gli stessi mezzi produttivi. La procedura consiste in:

1. raccolta dei dati tramite "from-to-chart" e fogli operativi mono e multi-prodotto;
2. ordinamento dei cicli di produzione;
3. costruzione delle carte PFA che rappresentano la descrizione dei cicli dei vari prodotti;
4. raggruppamento delle lavorazioni (clustering).

Nella realtà industriale odierna le aziende sono portate dalla variabilità del mercato alla produzione di ampi mix di prodotti. Questo fattore contrasta con l'esigenza di raggruppare i particolari in famiglie (se si sceglie di impostare la produzione seguendo i dettami della Group Technology). Spesso si è quindi chiamati a ricercare difficili compromessi tra queste due esigenze attraverso attività di:

- razionalizzazione del progetto;
- razionalizzazione del processo ovvero del ciclo tecnologico;
- aggiornamento, semplificazione della gamma produttiva.

Attività di razionalizzazione del progetto

Essa consiste nella razionalizzazione, standardizzazione e modularizzazione dei progetti e dei disegni costruttivi, tendente alla riduzione del numero dei particolari e alla unificazione nell'ambito dei rimanenti.

Razionalizzazione e standardizzazione dei cicli tecnologici

Tendente ad elaborare un ciclo standard per ogni famiglia di pezzi con riferimento ad un pezzo caratteristico (facente parte della famiglia o virtuale) il cui ciclo tecnologico sia comprensivo di tutte le operazioni dei cicli di tutti gli altri pezzi della famiglia a parità di sequenza operativa e di metodi di produzione. Per i singoli pezzi da realizzare variano solo i dati numerici del ciclo e possono mancare al più alcune operazioni rispetto a quelle previste dal ciclo tecnologico del pezzo caratteristico[1].

1.4.2 FMS - Flexible Manufacturing System

I sistemi FMS rappresentano tutt'oggi la risposta più soddisfacente per quanto riguarda la fabbricazione di ampi mix di prodotti in piccoli lotti.

Sono generalmente costituiti da celle di macchine operatrici a controllo numerico computerizzato servite da sistemi automatici di movimentazione dei pezzi e di movimentazione degli utensili in grado di eseguire una gamma di differenti operazioni su materie prime o semilavorati.

Tali celle di fabbricazioni sono dislocate in linea e sono servite da un sistema di movimentazione dei materiali, ad esempio un convogliatore o un sistema di carrelli automatici, sul quale si muove il mix produttivo. Il trasferimento logistico dei vari pezzi da una cella all'altra ed il funzionamento delle celle medesime viene gestito attraverso una opportuna rete gerarchica di calcolatori (Figura 1.6).

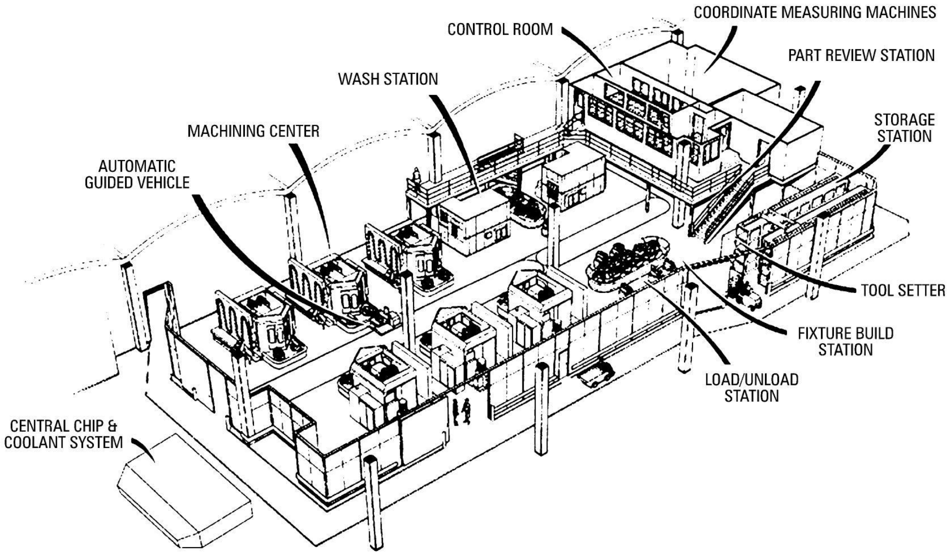

Figura 1.6: Esempio di sistema FMS.

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[1] *Prodotto caratteristico*: prodotto il cui ciclo produttivo comprende i cicli produttivi di altri prodotti.

I principali vantaggi conseguiti all'introduzione di un FMS sono:

- massima flessibilità nel modificare l'output produttivo, per adeguare lo stesso il più rapidamente possibile alle richieste del mercato;
- riduzione dei magazzini di reparto dei pezzi grezzi e semilavorati;
- riduzione dei costi di manodopera diretta ed indiretta;
- riduzione dei tempi di sosta del materiale in produzione;
- riduzione di attrezzature, maschere e utensili;
- ottimizzazione del carico macchina e del flusso produttivo;
- riduzione dei tempi di produzione;
- possibilità di lavorare su tre turni, anche in maniera non presidiata;
- riduzione dello spazio di layout occupato;
- miglioramento della qualità, particolarmente in termini di costanza.

É chiaro che la flessibilità si paga in termini di potenzialità produttiva e di costo di investimento. Relativamente al diagramma P-Q illustrato in precedenza (Figura 1.4), i sistemi FMS sono una risposta al problema della produzione relativamente alla zona III, mentre nella zona I (alte potenzialità e mix ridotto) il loro uso non è appropriato.

1.4.3 Elementi costitutivi di un sistema FMS

In generale un sistema FMS è costituito da:

- *macchine operatrici* che realizzano le lavorazioni sui pezzi;
- *sistemi di alimentazione/scarico* dei pezzi alle macchine e di movimentazione dei pezzi fra le macchine;
- sistemi per la gestione degli *utensili*;
- *logiche di controllo* per l'integrazione dei differenti dispositivi.

1.4.3.1 Macchine operatrici

Le macchine operatrici rappresentano il cuore del sistema, sono fondamentalmente riconducibili a 3 grandi famiglie di attrezzature:

1. macchine che eseguono lavorazioni assial-simmetriche: possono essere monomandrino o multimandrino. Possiedono un magazzino utensili con elevato numero di vani (anche 200). Per applicazioni di piccole e medie dimensioni sono preferibili quelle ad asse orizzontale, per le grandi dimensioni quelle ad asse verticale (Figura 1.7).
2. macchine per lavorazioni lungo le coordinate, detti centri di lavorazione rettilinea (Figura 1.8): sono deputate all'asportazione di materiale con moti

relativi rettilinei; dispongono di un magazzino utensili multiplo; le ultime realizzazioni controllano fino a 12 assi in simultanea consentendo quindi lavorazioni anche molto complesse.

3. macchine speciali, con questo termine si fa riferimento a tutte quelle macchine non inquadrabili nelle due precedenti categorie (Figura 1.9).

Figura 1.7: Macchina per lavorazione assial-simmetrica.

Figura 1.8: Centro di lavorazione rettilinea ad asse verticale.

1.4.3.2 Sistemi di movimentazione dei pezzi

All'interno di un sistema FMS i pezzi fluiscono in modo automatico. Per garantire questo flusso una rilevanza particolare è assunta dai sistemi di sostegno dei pezzi ovvero i *pallet portapezzo* e *le attrezzature*. I pallet possono avere una duplice funzione:

- sostenere ed ordinare i pezzi durante la fase di trasporto da una macchina all'altra (tipico dei centri di lavorazione assial-simmetrici);

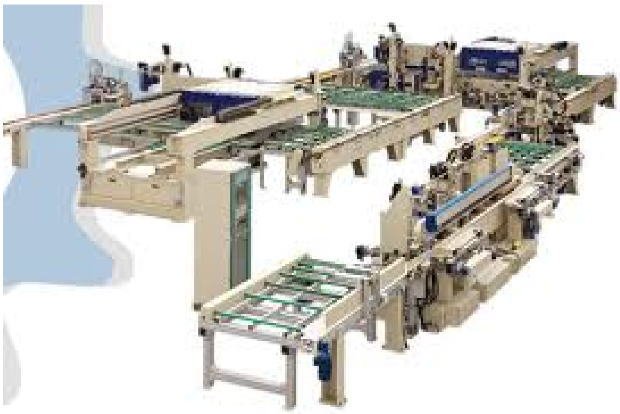


Figura 1.9: Centro di lavorazione del legno.

- sostenere ed ordinare i pezzi sia nella fase di trasporto ma anche in quella di lavorazione in macchina (tipico dei centri di lavorazione lungo le coordinate).

Il pallet può essere montato in macchina secondo concezioni alternative (Figura 1.10):

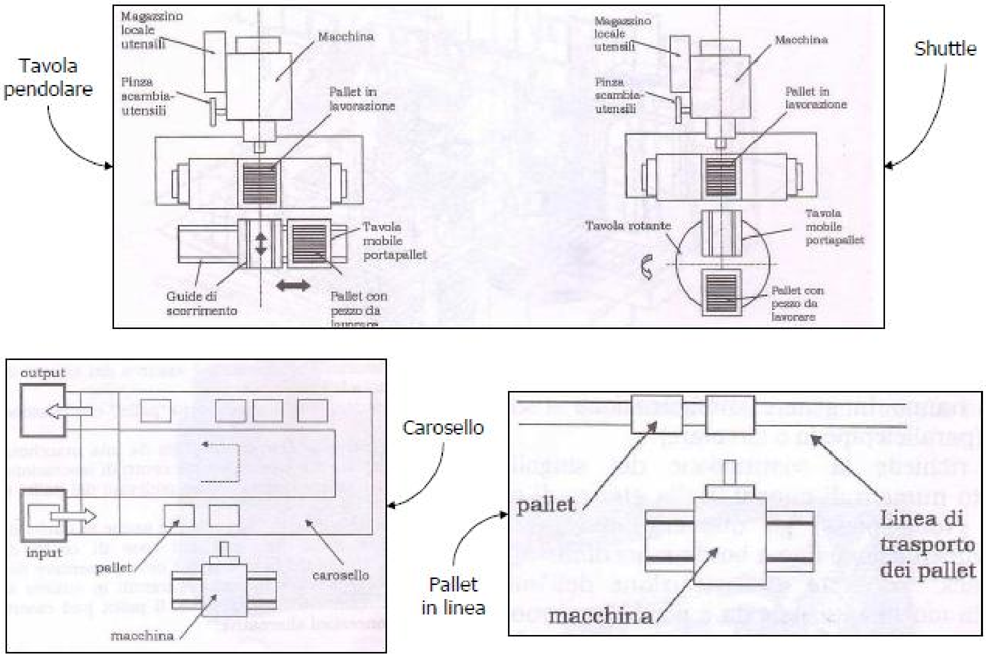


Figura 1.10: Sistemi di movimentazione.

- alimentazione a tavola pendolare: la tavola portapallet della macchina esegue un moto pendolare per portare sulle slitte di lavoro un pallet con pezzo

grezzo. In tempo mascherato (si lavora sulla tavola pendolare mentre la macchina esegue il ciclo) si provvede all'evacuazione del pezzo lavorato e alla sua sostituzione con un nuovo grezzo;
- alimentazione mediante shuttle: una navetta rotante a due posizioni scambia con la tavola della macchina il grezzo con il finito;
- alimentazione mediante robot caricatore: un robot si occupa dello scambio pallet (nei casi di centri di lavorazione assialsimmetrica);
- alimentazione con magazzino locale a carosello: a bordo macchina è previsto un carosello che realizza uno stoccaggio di un certo numero di pallet: questo può permettere il lavoro non presidiato per un certo intervallo di tempo;
- alimentazione di linea: variante rispetto allo schema a carosello, prevede l'installazione dei centri di lavoro direttamente sulla linea di trasporto del materiale.

Tipologie strutturali di pallet: pallet universali e pallet dedicati

Pallet universale: può essere adeguato allo specifico pezzo con staffagli e attrezzature mobili.
Pallet dedicato: ottimizzato nella geometria per il pezzo per renderne più veloce l'impiego nella fase di bloccaggio/sbloccaggio.

La scelta dipende da una valutazione economica principalmente legata alla numerosità dei lotti e delle lavorazioni. In questi ultimi anni il mercato tende lievemente a preferire le attrezzature dedicate o personalizzate.

1.4.3.3 Sistemi per la gestione degli utensili

Le esigenze di automazione flessibile degli FMS impongono la sostituzione rapida e programmata degli utensili durante i cicli di lavoro. Gli utensili sono contenuti in magazzini disposti all'interno della macchina operatrice, questi magazzini locali hanno in genere configurazione a catena Figura 1.11a o a rack Figura 1.11b. Gli schemi operativi di sostituzione dell'utensile sono numerosi ma tutti riconducibili all'uso di una navetta a doppia pinza che preleva dal magazzino l'utensile per la nuova lavorazione, si avvicina al mandrino ne scarica l'utensile in uso e monta quello per la lavorazione successiva. Fra i sistemi di controllo di cui è equipaggiata una linea FMS rivestono grande importanza i sistemi di rilevamento dell'usura e della rottura degli utensili.

(a) *catena*. (b) *rack*.

Figura 1.11: Tipologia di magazzino utensili.

1.4.3.4 Logiche di controllo

Un sistema complesso come un FMS può funzionare correttamente solo se sostenuto da un adeguato sistema di gestione delle informazioni. La struttura modulare del sistema ha favorito la sviluppo di una rete di controllo a schema gerarchico tradizionalmente si individuano 4 livelli:

1. controllo locale del mezzo produttivo: costituito da computer industriale o da PLC (Programmable Logic controller), è installato a bordo dei singoli mezzi produttivi e ne gestisce la funzionalità (Figura 1.12);

Figura 1.12: Console di comando/controllo locale.

2. controllo di cella-sistema di alimentazione pezzi: costituito ancora da computer industriale o PLC, gestisce rispetto ai mezzi produttivi le risorse ausiliarie, quali:
    - mezzi di movimentazione pezzi;
    - stazioni di carico-scarico;
    - eventuali stazioni di lavaggio.

3. DNC (Direct Numerical Control): il DNC rappresenta un sistema centralizzato per l'ottimizzazione della gestione in tempo reale del FMS. Il controllo DNC sovrintende tutto il funzionamento del sistema FMS, integrando il controllo delle varie isole, dei sistemi di movimentazione intra-isola di tutte le altre attività di linea;
4. CIM: il livello gerarchico più elevato è rappresentato dal CIM (Computer integrated Manufacturing): esso prevede la completa integrazione del FMS e del relativo DNC con il sistema informativo aziendale. In particolare il DNC può essere collegato con un host-computer di livello più elevato che gestisce a livello centralizzato le varie attività aziendali coordinate intorno ad un unico Data Base. A questo livello di automazione comincia a delinearsi nelle sue strutture fondamentali la fabbrica automatica.

1.4.4 Progettazione di un sistema FMS

La progettazione ed il corretto dimensionamento di un sistema FMS è fondamentale per la remunerazione dei notevoli investimenti necessari. Nel corso del tempo si è andato consolidando un approccio basato su alcuni passi fondamentali:

- applicazione della Group Technology per la determinazione del mix di prodotti potenzialmente producibili mediante il sistema FMS;
- calcolo delle risorse necessarie basato su modelli a valori medi e relativa determinazione della configurazione planimetrica;
- modellizzazione dinamica del sistema per la calibrazione dello stesso, in modo da correggere eventuali problemi di congestioni dovuti al comportamento dinamico del sistema;
- valutazione economica della validità dell'iniziativa.

Applicazione della group technology

La flessibilità di un sistema FMS consente la realizzazione di mix molto ampi di prodotti richiesti in piccole quantità. L'obiettivo di questa indagine è quello di individuare un certo numero di famiglie di prodotti simili, realizzabili con lo stesso sistema flessibile di produzione, tali da rappresentare una numerosità di pezzi così elevata da saturare la capacità produttiva del sistema e rendere vantaggioso il costo al pezzo.

Calcolo delle risorse necessarie e disposizione planimetrica

L'obiettivo di questa fase è il calcolo del numero di risorse necessarie per la realizzazione delle famiglie di prodotti individuate. In secondo luogo risulta necessario studiare il problema della disposizione planimetrica delle risorse determinate.

Per quanto riguarda il calcolo del numero di macchine di lavoro, si tratta di determinare il parco macchine necessarie per produrre le quantità Q_{ij} (pezzi/anno) di pezzi tipo j da realizzare sulla macchina tipo i. Dove con $j = 1, 2, \ldots, n$ si è indicato il mix di parti differenti da produrre e con $i = 1, 2, \ldots, m$ il set di macchine.

I pasi richiesti sono:

① studio dei cicli di lavorazione di ogni parte compresa nel mix;

② calcolo del numero $Z(i) = \dfrac{H(i)}{H_d}$ di macchine necessarie per il mix di parti.

dove:

H_d	ore effettivamente rese disponibili all'anno per la lavorazione di tutte le parti j sulla macchina i
$H(i)$	ore macchina all'anno relative ad ogni tipologia di macchina (ore/anno)

con:

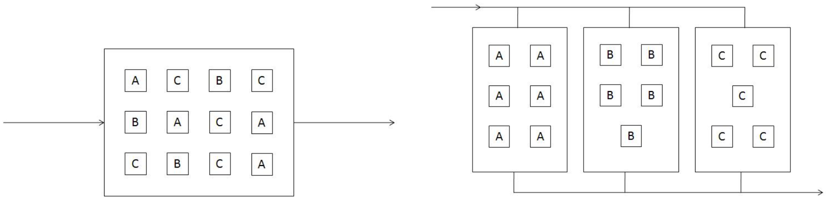
$$H(i) = \frac{\sum_{j=1}^{n} \left[\dfrac{t(i,j)}{C_S(i,j)} \cdot Q_{ij} + TPM(i,j) \cdot N_l(i,j) \right]}{A(i) \cdot C_u \cdot C_o}$$

in cui:

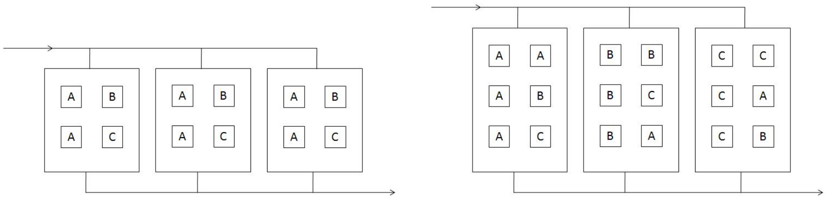
$t(i,j)$	tempo teorico di ciclo della macchina i per produrre la parte j (ore/pezzo);
Q_{ij}	produzione di pezzi/anno j richiesta sulla macchina i;
$C_S(i,j)$	coefficiente di scarto della parte j lavorato sulla macchina i (pezzi buoni/pezzi prodotti);
$TPM(i,j)$	tempo teorico di preparazione (set-up) della macchina i per lavorare la parte j;
$N_l(i,j)$	numero previsto di lotti all'anno della parte j da lavorare sulla macchina i;
$A(i)$	coefficiente di disponibilità della macchina i $\quad A(i) = \dfrac{UT}{UT + DT}$;
UT	Up Time: tempo in cui la macchina è in grado di eseguire la propria funzione;
DT	Down Time: tempo di fuori servizio dovuto a manutenzione, guasti, etc.;
C_u	coefficiente di conduzione: tiene conto del rendimento dell'operatore, delle perdite di tempo per mancanza di motivazioni, condizioni di lavoro sfavorevoli, condizioni ambientali non gradite, etc. (< 1);
C_o	coefficiente organizzativo, tiene conto della inefficienza organizzativa della produzione (< 1);

Per quanto riguarda le altre risorse (magazzino, stazioni carico-scarico, etc.) si tratta di scelte strettamente legate al caso reale, da valutare di volta in volta. Il progetto del sistema di trasporto è strettamente legato alla disposizione planimetrica delle attrezzature di lavoro. Differenti sono le modalità con cui si possono disporre le celle di lavoro:

- *disposizione random*: adatto per basse numerosità di macchine $(3, 4)$, in genere porta a linee di movimentazione dei pezzi lunghe e tortuose (Figura 1.13a);
- *disposizione funzionale*: le macchine sono raggruppate per funzione, in pratica è l'automatizzazione del concetto del job-shop (Figura 1.13b);
- *disposizione modulare*: i mezzi sono strutturali in celle di lavoro (di solito uguali) impiegate in parallelo (consente l'espansione modulare) (Figura 1.13c);
- *disposizione cellulare*: è la disposizione che meglio si adatta al concetto di Group Technology, ciascuna cellula elementare contiene una o un gruppo di macchine "particolarmente dedicate" alla realizzazione di una famiglia (Figura 1.13d).



(a) *Random*. (b) *Funzionale*.



(c) *Modulare*. (d) *Cellulare*.

Figura 1.13: Layout.

Per ciascuna di queste disposizioni il flusso dei materiali è legato alla posizione reciproca delle macchine. In questo senso un'accurata analisi può portare a dei notevoli risparmi economici e all'eliminazione di problemi di congestione del traffico. Per questo studio si può adottare l'approccio Hollier (Vedere [10]).

Il metodo prende le mosse dalla conoscenza del flusso dei materiali fra le macchine della cella, quindi dalla conoscenza delle *From-To chart* (Foglio Da/A). Sommando le quantità per riga e per colonna si ottengono rispettivamente il numero di pezzi uscenti dalla macchina in esame (Da) ed il numero di pezzi entranti nella macchina in esame (A). Quindi per ciascuna macchina è possibile calcolare il rapporto Da/A. L'ordine delle macchine può essere stabilito per valori decrescenti di tale rapporto (si mettono prima le macchine a flusso prevalente uscente). Una volta determinata la disposizione delle attrezzature si può procedere alla scelta del sistema di trasporto (non ci sono metodologie generali).

Modellizzazione dinamica del sistema
Un FMS è un sistema molto complesso, governato da un numero molto elevato di variabili che hanno caratteristiche di dinamicità molto forte. Dopo aver effettuato il progetto di massima è assolutamente necessaria una valutazione del comportamento dinamico del sistema. Questo si può condurre attraverso la costruzione di modelli simulativi che permettono la verifica dei principali dimensionamenti effettuati alla luce dei transitori e delle congestioni del sistema.

Serve per:

- verificare se è raggiunto il livello produttivo richiesto sul mix;
- controllare la saturazione di tutte le risorse;
- correggere eventuali problemi introdotti dal fattore "tempo" sul sistema.

Valutazione economica dell'iniziativa
Alla fine di uno studio di carattere tecnico, vista l'entità delle risorse economiche in gioco, è assolutamente necessaria la valutazione economica dell'iniziativa. Si tratta di costruire il piano iniziale di investimento e provvedere alla stima dei flussi di cassa annui alla luce dei dati ottenuti dal progetto (Vedere [47]).

1.5 Mezzi logistici nell'assemblaggio automatico

Molti prodotti vengono realizzati attraverso attività di fabbricazione di parti e successivo assemblaggio (o montaggio) di queste. Anche i sistemi di montaggio dovranno possedere un livello di automazione e flessibilità correlato alle quantità e all'ampiezza del mix produttivo richiesto dal mercato.

1.5.1 Complessità del prodotto - struttura modulare

Un elemento rilevante nel processo di montaggio è la complessità del prodotto in quanto il livello di difficoltà del montaggio è ad essa proporzionale. In base alla complessità si distinguono diverse stazioni di lavoro:

- *montaggio a posto singolo*: grazie a un numero ridotto di elementi i prodotti vengono montati completamente in posti di lavoro singoli;
- *montaggio suddiviso*: in presenza di prodotti complessi con un elevato numero di componenti, conviene frazionare i processi di montaggio.

Un presupposto dello smembramento dei prodotti complessi è costituito dal fatto che il prodotto sia strutturato in modo tale da permettere il montaggio preliminare di cosiddetti "gruppi costruttivi" (Figura 1.14).

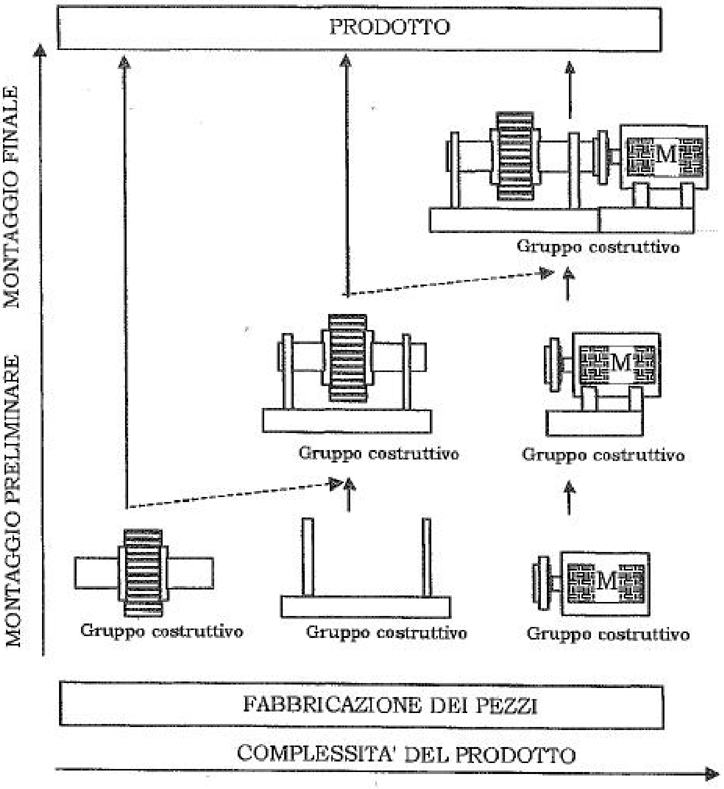


Figura 1.14: Esempio di scomposizione in gruppi costruttivi.

Per una strutturazione conforme al montaggio dei gruppi costruttivi e dei prodotti finiti è necessario osservare le seguenti regole fondamentali:

- l'intero processo di montaggio deve essere suddiviso in settori o "gruppi costruttivi";
- l'intero processo di montaggio deve essere chiuso e completo in se stesso, in modo che la sua manipolazione corrisponda a quella di un singolo pezzo;
- un gruppo costruttivo deve poter essere collaudato separatamente;
- ciascun gruppo costruttivo deve presentare il minor numero possibile di collegamenti con altri gruppi;
- i gruppi costruttivi che cambiano in funzione delle varianti del prodotto non devono essere raggruppati insieme a quelli uguali per tutte le varianti;
- i gruppi costruttivi delle varianti devono presentare le stesse condizioni di montaggio.

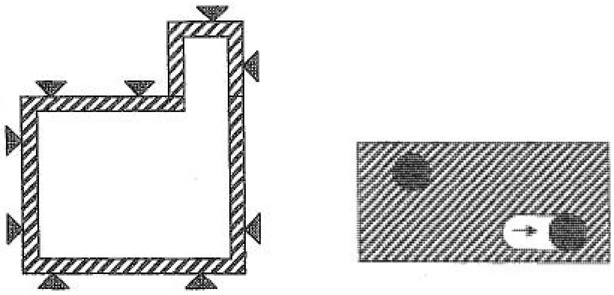
Per l'osservanza di queste regole è di importanza fondamentale la creazione della cosiddetta *unità di base* per i singoli gruppi costruttivi e per il prodotto finito.

1.5.2 Unità di base

Con unità di base si intende il singolo pezzo di base su cui nel corso del processo di montaggio vengono poi montati gli altri elementi componenti. Essa deve essere strutturata in modo da rendere possibile il trasferimento da una stazione di montaggio all'altra senza necessità di attrezzi particolari.

Questa esigenza non può essere soddisfatta in tutti i casi; tuttavia almeno per quanto riguarda il montaggio manuale in cui si lavora senza attrezzi, tale condizione deve essere considerata come obiettivo. Nel caso delle catene di montaggio, con attrezzi portanti o nel montaggio automatizzato con supporti dei pezzi, la funzione di unità di base può essere in parte svolta dagli attrezzi portanti o di supporto. Un esempio classico di unità di base nell'elettronica è il circuito stampato su cui vengono poi montati tutti gli altri componenti.
Nel caso di montaggio con supporti dei pezzi, le unità di base devono essere progettate in modo da poter eseguire automaticamente il centraggio. La precisione del centraggio dell'unità di base sul supporto è estremamente importante quando si esegue il montaggio suddiviso. Le piastre e gli alloggiamenti intesi come unità di base devono essere configurati in modo che:

- **centraggio esterno**: le tolleranze esterne possono essere scelte consentendo un posizionamento preciso nei punti di unione all'interno dell'unità di base (Figura 1.15a);
- **centraggio interno**: nel caso di azione esterna possono essere precluse certe attività lungo il perimetro e le superficie esterne del componente, l'unità di base può essere bloccata internamente attraverso appositi fori (Figura 1.15b).



(a) *esterno.* (b) *interno.*

Figura 1.15: Centraggio.

1.5.3 Numero di componenti

Direttamente collegato alla complessità del prodotto, il numero di componenti rappresenta un elemento critico per l'assemblabilità del prodotto finale. In generale bisogna ottenere il miglior compromesso fra:

- la necessità di ridurre il numero di componenti per facilitare le operazioni di montaggio;
- la necessità di limitare il ricorso a particolari unici ma costruttivamente molto complessi e difficili da realizzare.

Con riferimento al montaggio l'uso dei materiali e dei metodi di produzione moderni permette la configurazione strutturale in un solo pezzo di prodotti che prima dovevano essere fabbricati assemblando più componenti (Figura 1.16).

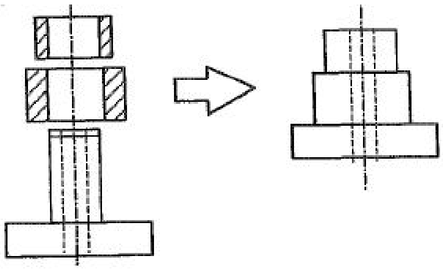


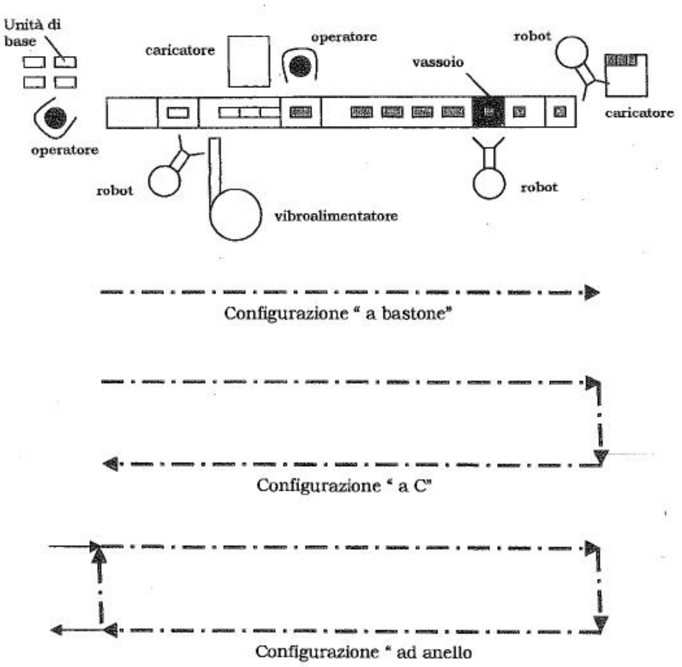
Figura 1.16: Riconfigurazione di 3 pezzi in 1 solo pezzo.

1.5.4 Architetture di una linea di assemblaggio

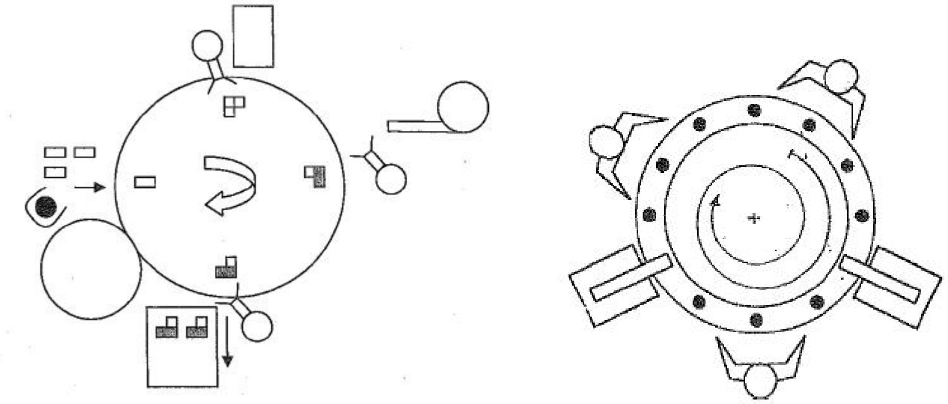
Le linee di assemblaggio dedicate al montaggio dei componenti hanno 2 architetture principali:

1. **Configurazione rettilinea**: le stazioni di lavoro sono allineate unite tra loro da un sistema di trasporto di tipo transfer. In relazione al numero di stazioni e quindi agli ingombri si possono avere schemi a *bastone*, a C o ad *anello* (Figura 1.17a);
2. **Configurazione circolare**: il sistema di trasferimento dei pezzi fra le stazioni è rappresentato da una *tavola rotante* Figura 1.17b.
   I particolari sono solidali a questa tavola che avanza di un passo ad intervalli di tempo, eseguendo una rotazione elementare e trasferendo i pezzi da una stazione a quella seguente. Lo schema circolare a parità di stazioni di lavoro ha:
   - minore ingombro;
   - schema più compatto.

Peraltro non consente l'introduzione di un numero molto elevato di stazioni. Per attenuare questo limite si sono introdotte le *tavole multigiro* Figura 1.17c. In questo caso il pezzo viene completato con un numero di giri della tavola superiore ad 1. Quindi la flessibilità dei mezzi operativi in una determinata posizione angolare è un prerequisito imprescindibile, in quanto in relazione al numero del giro in questione devono eseguire un differente lavoro sul particolare.



(a) *rettilinea*.



(b) *circolare*.

(c) *circolare multigiro*.

Figura 1.17: Linea di assemblaggio.

Si definisce *cadenza* di una stazione di lavoro il tempo fra l'uscita di due prodotti consecutivi dalla stazione stessa. Le linee di assemblaggio possono essere progettate:

1. a *cadenza imposta*: tutte le stazioni di lavoro hanno la medesima cadenza e quindi lo stesso tempo di ciclo per eseguire un'operazione:
    - utilizzate quando vi è bassa incidenza di operazioni manuali;
    - utilizzate con schema circolare;
2. a *cadenza non imposta*: le stazioni lavorano con tempi di ciclo differenti e quindi sorge il problema della loro armonizzazione o bilanciamento attraverso l'inserimento di polmoni:
    - utilizzate quando vi è alta incidenza di operazioni manuali;
    - utilizzate con schema rettilineo.

1.5.5 Elementi costitutivi di una linea flessibile di assemblaggio

I principali elementi presenti in una linea flessibile di assemblaggio FAS (Flexible Assembly System) sono:

- attrezzi portanti del pezzo;
- sistema di trasporto dei pezzi;
- sistema di alimentazione dei componenti da montare;
- stazioni di lavoro;
- stazioni di controllo e collaudo dei montaggi.

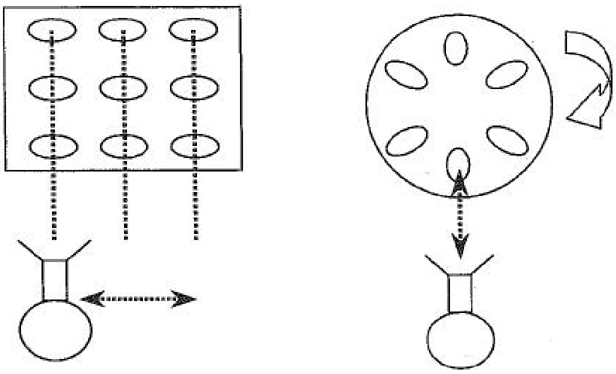
1.5.5.1 Attrezzi portanti del pezzo

Il pezzo base deve essere trasferito fra le stazioni di lavoro in modo da "crescere" tramite i successivi montaggi di parti componenti fino a diventare il prodotto finito. Il pezzo base per poter essere trasferito e centrato viene riferito a un *attrezzo portante* (definito anche pallet, vassoio, supporto) che verrà movimentato dal sistema di trasporto.

In alcuni casi il vassoio oltre al pezzo portante può anche contenere altre parti del prodotto finito che poi nelle stazioni di lavoro verranno via via assemblate. Si parla in questo caso di "kit" di componenti disposti sul pallet.

I vassoi possono contenere un pezzo base ovvero essere multipli cioè contenere più pezzi base. Nel caso di vassoi multi-pezzo sono impiegabili 2 modalità di lavoro:

- attraverso attrezzi portanti semplici con pezzi allineati in differenti posizioni (Figura 1.18a);
- attraverso attrezzi portanti circolari con possibilità di movimento di rotazione in modo da presentare il pezzo da lavorare sempre nella stessa posizione (Figura 1.18b).



(a) *con pezzi allinati.* (b) *circolare.*

Figura 1.18: Attrezzo portante.

1.5.5.2 Sistemi di trasporto degli attrezzi portanti

Trattando il tema dei sistemi di trasferimento degli attrezzi portanti implicitamente si fa riferimento a linee di assemblaggio rettilinee. Nel caso di inserimento di postazioni manuali di lavoro, al sistema di trasporto è richiesta anche la capacità di realizzare il magazzino interoperazionale (necessario per svincolare i diversi tempi di lavorazione).

Questo requisito può essere ottenuto mediante:

1. sezionamento del sistema di trasporto in tante unità elementari controllabili separatamente da opportuni attuatori e sensori in modo da avere moto solo in caso di possibilità di avanzamento del pezzo (Figura 1.19);

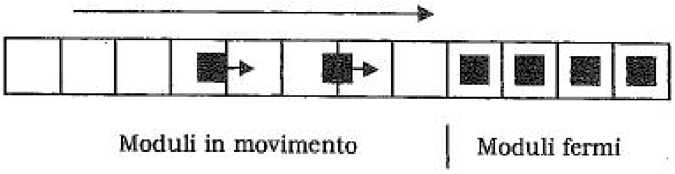


Figura 1.19: Esempio di sezionamento del sistema di trasporto.

2. impiego di attuatori con trasmissioni a frizione che al raggiungimento di un certo sforzo disaccoppiano il sistema di trasporto dall'attuatore. In questi sistemi il polmone si ottiene automaticamente: in quanto i pezzi si adagiano uno contro l'altro, essendo fermi fanno crescere lo sforzo delle motorizzazioni fino al livello di soglia, "sganciando" così le trasmissioni di moto (Figura 1.20);
   Uno sviluppo ulteriore di questa soluzione, prevede l'eliminazione della trasmissione a frizione a favore di sistemi *dissipativi*: un'opportuna scelta

Figura 1.20: Esempio di sezionamento del sistema di trasporto.

dei materiali dei sistemi di trasporto permette di ottenere per attrito il moto in condizioni di via libera e lo stazionamento in situazioni di immagazzinamento a causa della via occupata. Nella pratica industriale i sistemi più impiegati sono:

- a catene (Figura 1.21a);
- a rulli (Figura 1.21b);
- a nastro (Figura 1.21c);
- a tapparelle (Figura 1.21d).

(a) *a catena*. (b) *a rulli*.

(c) *a nastro*. (d) *a tapparella*.

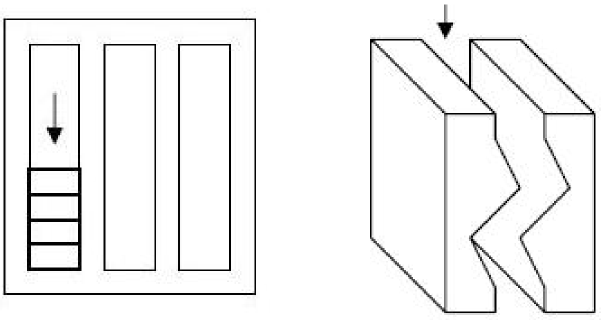
Figura 1.21: Sistemi di trasporto

1.5.5.3 Sistemi di alimentazione dei componenti

Nelle stazioni di lavoro delle linee di assemblaggio vengono eseguiti dei montaggi fra componenti e gruppi costruttivi che possono essere direttamente posizionati sul pallet oppure possono provenire dall'esterno rispetto al vassoio stesso. Tendenzialmente i componenti di dimensioni ridotte oppure quelli variabili da prodotto a prodotto vengono alimentati dall'esterno.

Nel caso di impiego di dispositivi automatici di montaggio è auspicabile per semplificare e velocizzare le operazioni che il materiale sia alimentato in modo ordinato al dispositivo di montaggio. I sistemi di alimentazione, detti anche *caricatori*, si suddividono in:

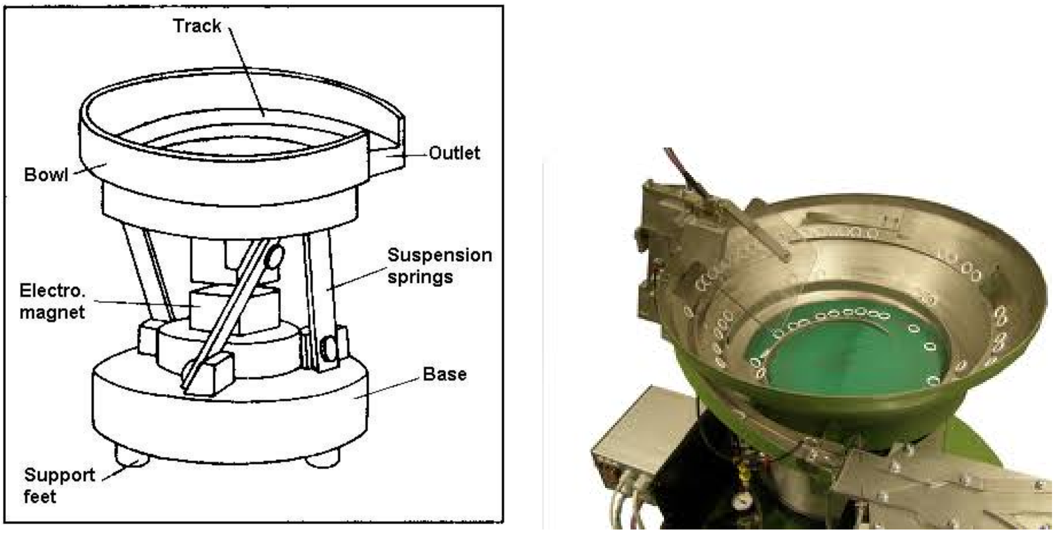
- caricatori piani (Figura 1.22a);
- caricatori a contenitore (Figura 1.22b);
- vibroalimentatori orbitali.



(a) *piano.* (b) *contenitore.*

Figura 1.22: Tipi di caricatore

Il dispositivo di alimentazione più diffuso nella pratica è il vibroalimentatore orbitale (Figura 1.23). Questo dispositivo è formato da un basamento pieno, appoggiato su tre piedini di gomma che assorbono le vibrazioni. Sulla circonferenza di questo basamento sono disposti in modo obliquo tre pacchi di molle a lamina che lo collegano con la lastra di supporto del contenitore dei pezzi. Nel contenitore si trovano i canali elicoidali che conducono all'uscita del vibroalimentatore. Le vibrazioni sono create da un magnete alimentato a corrente alternata. Nei canali elicoidali sono sistemati gli elementi che servono per ordinare i pezzi, chiamati anche deflettori o selezionatori di giaciture. Con il vibroalimentatore orbitale i pezzi possono essere depositati, ordinati e poi, in collegamento con le guide di uscita, inseriti in caricatori e trasportati. Grazie alla forma convessa del fondo e alle oscillazioni meccaniche provocate dall'elettromagnete, i pezzi disposti casualmente si spostano lungo il bordo del deposito. Il magnete azionato da corrente alternata genera forze di attrazione periodiche, cosicché il contenitore oscilla con una vibrazione prossima alla risonanza e in virtù della posizione inclinata delle molle durante la vibrazione si verifica un avanzamento dei componenti.



(a) *Schema.* (b) *Esempio.*

Figura 1.23: Vibroalimentatore orbitale

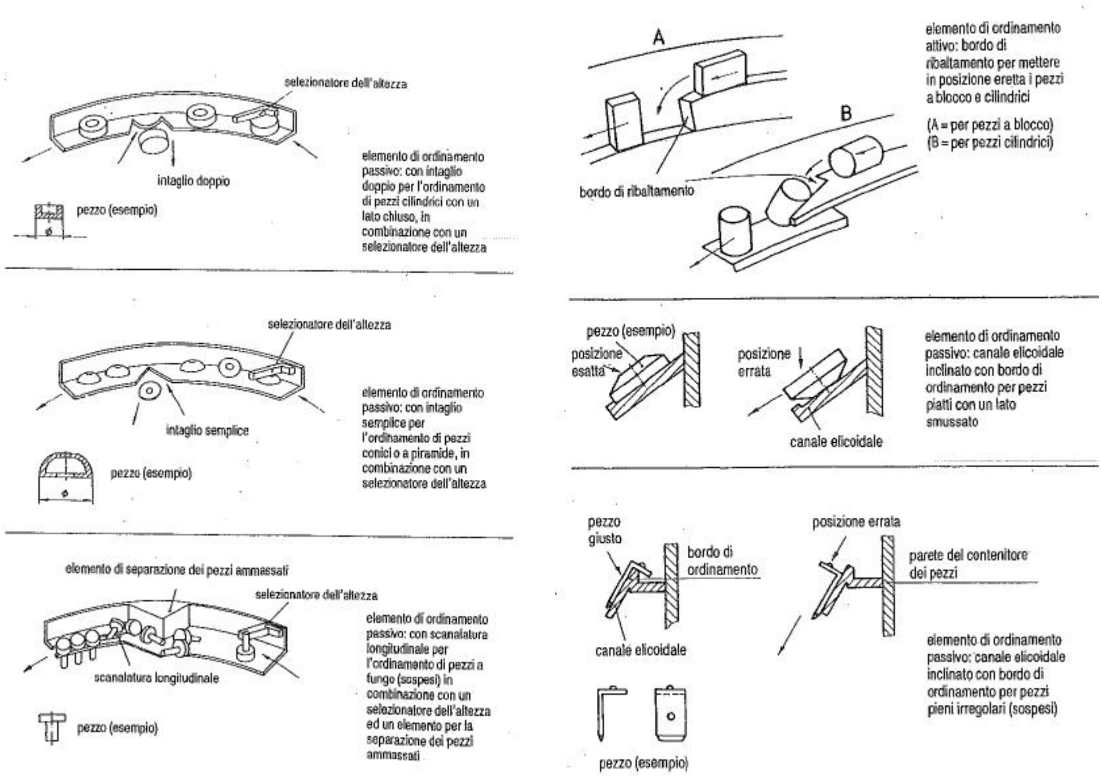
I pezzi vengono ordinati attraverso 2 sistemi:

1. ordinamento passivo: i pezzi in posizione scorretta vengono respinti e tornano a cadere nel contenitore di raccolta (Figura 1.24a);
2. ordinamento attivo: i pezzi vengono portati nella giusta posizione attraverso elementi di ordinamento disposti in serie e quindi non ricadono mai nel contenitore (Figura 1.24b).

Un presupposto fondamentale per poter ordinare i pezzi è che questi possano muoversi liberamente nell'area d'azione degli elementi di ordinamento, in modo da non ostacolarsi reciprocamente. Inoltre inserendo degli elementi di separazione è possibile evitare un afflusso troppo elevato di pezzi da ordinare.

Materiale a nastro continuo unito a un supporto

Nella pratica industriale talvolta sono da alimentare componenti che presentano delle forme "intricate" difficili da alimentare con i sistemi visti prima. In questi casi il metodo più sicuro di alimentazione è l'alimentazione di materiale in forma di striscia (Figura 1.25). Il componente viene alimentato come materiale continuo e separato dalla striscia solo al momento del montaggio. Il vantaggio di questo tipo di fornitura è il mantenimento dell'ordine dei pezzi e quindi l'ottenimento di una disponibilità molto elevata.



(a) *passivo*. (b) *attivo*.

Figura 1.24: Esempio di ordinamento

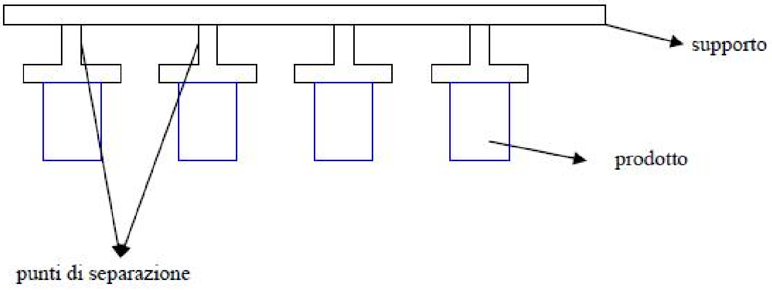


Figura 1.25: Materiale continuo.

Schema di una stazione di alimentazione dei componenti

La Figura 1.26 mostra una tipica stazione di alimentazione dei componenti alle stazioni di lavoro localizzate lungo una tavola di lavoro. Possiamo riconoscere:

- un vibroalimentatore orbitale;
- una guida elettromagnetica di uscita;
- una stazione di singolarizzazione;
- un manipolatore "pick and place", che trasferisce il componente proveniente dal singolarizzatore e lo colloca sul supporto del transfer della macchina di montaggio.

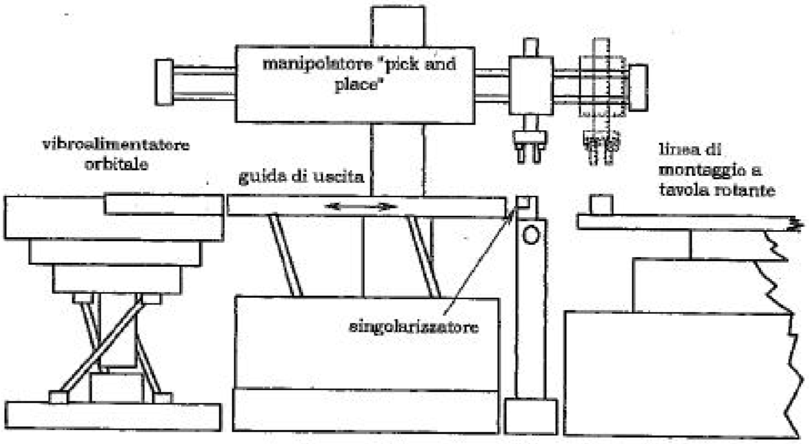


Figura 1.26: Struttura di una stazione di alimentazione dei pezzi.

Il grado di affidabilità del sistema è determinato dalla:

- qualità dei componenti;
- pulizia dei pezzi;
- disposizione e la precisione delle stazioni di alimentazione.

L'esperienza pratica ha evidenziato che i guasti più frequenti si verificano all'interno del vibroalimentatore orbitale e nel passaggio da quest'ultimo alla guida di uscita. Per garantire che i guasti non compromettano la disponibilità della macchina di montaggio, la lunghezza della guida di uscita deve essere dimensionata in modo da creare un effetto polmone tra i componenti ordinati, che si trovano nella guida di uscita. La capacità di questo polmone deve essere determinata in modo da permettere che i guasti siano individuati ed eliminati tempestivamente senza che la guida giri a vuoto. A tale scopo conviene prevedere un tratto di sicurezza nella guida di uscita, inteso come polmone, dotato di un opportuno sistema di rilevamento di segnali e di un corrispondente comando. La Figura 1.27 mostra la struttura schematica di un tratto di sicurezza.

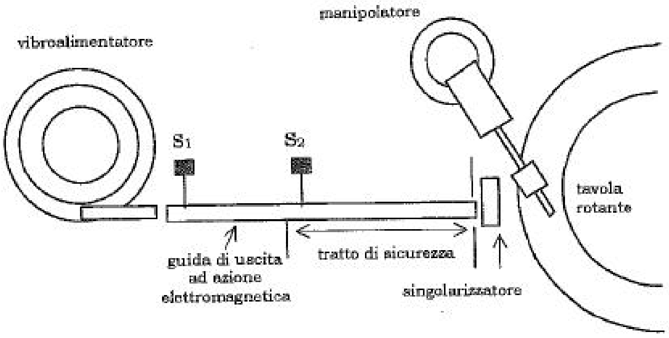


Figura 1.27: Struttura di un tratto di sicurezza.

Sulla guida di uscita devono essere installati due sensori S_1 e S_2:

- con il sensore S_1 il vibroalimentatore orbitale viene adattato alle prestazioni richieste. Se la guida di uscita scorre a pieno carico questa condizione viene rilevata dal sensore S_1 che disattiva il vibroalimentatore. Quando i pezzi vengono scaricati nel singolarizzatore attraverso il manipolatore e l'ultimo pezzo supera la stazione S_1 lo stesso sensore riattiva il vibroalimentatore;
- un secondo sensore S_2 viene disposto in modo tale che tra il sensore e la stazione di singolarizzazione ci sia un tratto di sicurezza con una certa capacità di polmone. Se il sensore S_2 registra che in quel punto non arrivano più pezzi traduce questa condizione in un segnale di allarme ottico o acustico. In questo modo l'addetto alla macchina viene avvertito che nell'area del vibroalimentatore si è verificato un problema.

Collocazione dei sistemi di alimentazione

In genere essi vengono collocati in modo ortogonale ai transfer rettilinei e in senso radiale sulle tavole circolari per limitare gli ingombri e soprattutto non precludere spazi per altri attrezzi (Figura 1.28). In alcuni casi però si è costretti ad impiegare soluzioni ibride e non ottimali.

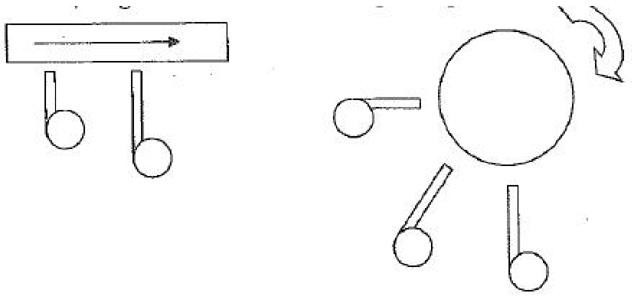


Figura 1.28: Disposizioni consigliate.

1.5.5.4 Stazioni di lavoro

Per quanto riguarda le stazioni ove effettivamente vengono realizzate le operazioni di montaggio si evidenzia una grande variabilità e differenziazione di tipologie. Sul piano della funzionalità operativa una prima osservazione riguarda la configurazione della stazione, in cui vi possono essere:

- dispositivi completamente automatici;
- operatori umani.

In genere gli alimentatori vengono posti sia per gli operatori umani che per i dispositivi automatici molto vicini alle zone di montaggio in modo da minimizzare i percorsi di presa e manipolazione delle parti, anche se con configurazioni diverse (Figura 1.29).

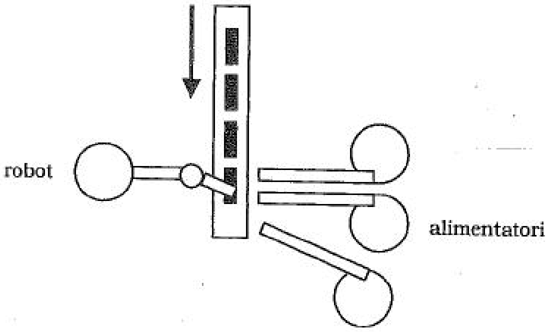


Figura 1.29: Schema di una stazione robotizzata.

Per l'uomo vengono definite 2 aree di operatività (Figura 1.30):

- l'area dei movimenti primari (AP)
- l'area dei movimenti secondari (AS)

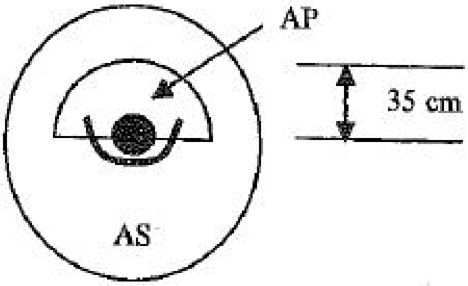


Figura 1.30: Aree di operatività.

Per eliminare il ricorso ad operazioni nell'area secondaria, vengono disposti i sistemi di alimentazione frontalmente e entro i 35 cm di distanza. Stazioni di lavoro manuali sono tipiche in linee non cadenzate, quindi risulta necessario l'inserimento di magazzini interoperazionali che permettano il disaccoppiamento delle cadenze di lavoro. La modalità più impiegata è la costruzione di un'area di lavoro ricavata in esecuzione deviata rispetto al transfer con l'intatta possibilità della via di corsa rettilinea. Il tratto deviato di transfer offre la possibilità di immagazzinare prodotti (Figura 1.31).

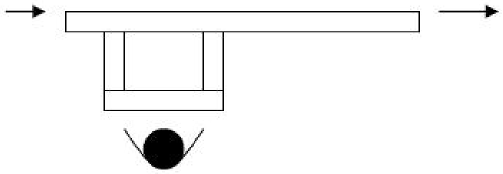


Figura 1.31: Isola di lavoro manuale in esecuzione deviata.

Altro aspetto rilevante per le stazioni di lavoro riguarda l'attrezzistica, che dipende dall'operazione da svolgere di volta in volta. Per quanto riguarda invece le postazioni di lavoro bisogna tenere in considerazione il tema della sicurezza.

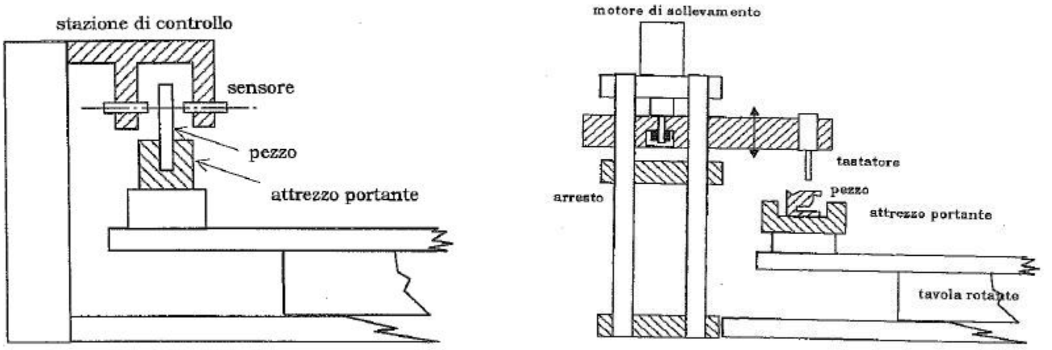
1.5.5.5 Stazioni di controllo

Durante le operazioni di montaggio l'unità in via di costruzione viene sottoposta a dei controlli per verificare la correttezza dello stato del Work In Progress (WIP). I risultati positivi provocano il "via libera" mentre i risultati negativi possono essere interpretati nei seguenti modi:

- disattivazione immediata: in questo caso qualora la macchina rilevi un errore essa procede all'immediato arresto della linea o comunque dei mezzi responsabili di quel montaggio;
- disattivazione della macchina dopo un certo numero di errori in sequenza: in questo caso il mezzo operativo viene disattivato solo dopo un certo numero di errori consecutivi;
- memorizzazione degli errori: questa modalità non prevede l'arresto della stazione di montaggio. In caso di errore il pezzo errato viene semplicemente reso riconoscibile per i dispositivi a valle che non lo utilizzeranno nelle successive fasi di montaggio.

Per quanto riguarda il tipo di struttura, le stazioni di controllo possono essere suddivise tra:

- stazioni che a causa della posizione dell'oggetto da esaminare, devono essere disposte in posizione fissa (Figura 1.32a);
- stazioni che, per svolgere i propri compiti, devono eseguire un movimento (Figura 1.32b).



(a) *fissa*.

(b) *mobile*.

Figura 1.32: Stazioni di controllo

1.5.6 Progettazione di una linea flessibile di assemblaggio automatico

La progettazione di una linea di montaggio automatico (FAS) richiede una attività piuttosto complessa, che, pur differenziandosi da prodotto a prodotto si può ricondurre allo sviluppo di alcune fasi tipiche.

1.5.6.1 Razionalizzazione del progetto dei prodotti secondo il Design For Assembling - DFA

Per ottenere un agevole montaggio automatico di un prodotto occorre che il progetto del prodotto stesso abbia delle caratteristiche intrinseche di semplicità che favoriscano le attività di montaggio. Quindi in fase di progetto bisogna:

1. effettuare delle scelte che semplifichino il ciclo di montaggio riducendo il numero delle parti nonché il numero e la difficoltà delle operazioni di montaggio da eseguire (si parla infatti di Design For Assembling - DFA);
2. applicare criteri di modularità e di semplificazione dei prodotti;
3. che le linee vengano raggruppate per famiglie di prodotti (Group Technology)

In letteratura si trovano tabelle che formalizzano alcuni principi progettuali per l'ottenimento di prodotti facili da montare (Vedere [2]). Per una analisi sistematica si può far ricorso alla cosiddetta "DFA house" introdotta da Rampersad (Vedere [48]).

1.5.6.2 Razionalizzazione del processo produttivo

Consiste nel progettare ed approntare processi di assemblaggio realizzabili e tecnologicamente simili per prodotti della stessa famiglia. In questo caso si possono cercare delle razionalizzazioni attraverso la modularità e la semplificazione dei cicli di assemblaggio.

1.5.6.3 Definizione del prodotto caratteristico

Consiste nell'individuazione del prodotto caratteristico, ossia un prodotto reale o fittizio, che presenta tutte le lavorazioni di tutti i prodotti della famiglia. In altre parole tutti i prodotti della famiglia si devono poter ottenere da quello caratteristico per eliminazione di fasi di lavoro (montaggio).

1.5.6.4 Determinazione dei tempi e dei metodi di montaggio

Per poter dimensionare le stazioni di lavoro bisogna definire le metodologie di montaggio e i tempi corrispondenti. La valutazione dei tempi può essere condotta sperimentalmente attraverso campagne di rilevazione sul campo di processi analoghi e successive elaborazioni statistiche dei risultati. La stima dei tempi di montaggio può essere svolta per via teorica attraverso la procedura Method Time Measurement - MTM. In base a questa procedura ciascuna azione di montaggio può essere scomposta in operazioni elementari a cui corrisponde un tempo standard. Sommando tutti i tempi elementari si ottiene una stima della durata della particolare attività di assemblaggio (Vedere [40]).

1.5.6.5 Scelta della cadenza della linea e dimensionamento delle stazioni

Le linee di assemblaggio possono lavorare con una cadenza imposta oppure libera. La scelta del tipo di cadenza viene attuata in relazione alla produttività richiesta ed alla componente di lavoro umano necessario per le particolari attività di montaggio previste.

In generale si ha:

- cadenza imposta in presenza di linee con elevata produttività e ridotta incidenza del lavoro umano;
- cadenza libera in presenza di numerose attività richieste all'operatore.

Scelta la cadenza bisogna distribuire il carico di lavoro in un certo numero di stazioni. L'obiettivo di questo bilanciamento è quello di ottenere il miglior compromesso economico fra costi diretti di montaggio (manodopera ed attrezzature) e i costi indiretti di mancato completamento di alcune operazioni, nel rispetto dei vincoli tecnologici e produttivi presenti. Nel caso di linee a cadenza imposta viene impiegato il metodo euristico di Kottas Lau. Nel caso di linee a cadenza libera si esegue una ricerca del bilanciamento che riduce al minimo l'ammontare degli ozi per i mezzi produttivi.

Nella pratica industriale il parametro di valutazione del bilanciamento ottimale è dato dal minimo costo unitario di montaggio.

1.5.6.6 Scelta del sistema di trasporto e di alimentazione dei componenti

Si passa ora alla scelta del sistema di trasporto per la movimentazione dei pezzi e/o degli attrezzi portanti lungo le varie posizioni di montaggio. La presenza di stazioni manuali implica il dimensionamento dei polmoni fra le diverse stazioni (in pratica realizzati sul sistema di trasporto). Quindi a questo stadio della progettazione si effettua la scelta del tipo e della collocazione fisica dell'insieme dei caricatori e alimentatori. In pratica il risultato di questa fase è il progetto di dettaglio delle strutture fisiche della linea attraverso disegni, tabelle, schemi, etc.

1.5.6.7 Verifica della flessibilità e simulazione

Prima di procedere alla valutazione economica dell'investimento è bene quindi verificare se la linea ideata rispetta le richieste in termini di flessibilità. In pratica si tratta di controllare la "montabilità" di tutti gli elementi della famiglia. Questo controllo può sanare eventuali lievi imprecisioni introdotte dalle possibili differenze tra il progetto concettuale e le attrezzature fisiche realmente scelte. Inoltre è consigliabile un approccio simulativo per la verifica del comportamento dinamico in condizioni di transitorio, per la determinazione della capacità richiesta dai polmoni per poter cogliere gli obiettivi produttivi prefissati.

1.5.6.8 Valutazione economica dell'investimento

La linea di assemblaggio è fattibile se presenta una adeguata convenienza economica a questo scopo alla fine del progetto bisogna determinare, attraverso la valutazione dei costi di installazione e di esercizio delle attrezzature scelte, il ritorno economico dell'investimento (attraverso il calcolo del VAN, TIR, tempo di recupero) e il costo unitario stimato di montaggio.

Capitolo 2

FLEXIBLE AUTOMATION STATE OF THE ART

THE DEMAND for customized products has been increasing continuously in the recent years and a great deal of attention has been given to the automation of manufacturing and assembly systems. In order to meet increased demand for customized products and to reduce production lot sizes, the industry has adapted new techniques and production concepts by introducing flexibility into production machines (2.1) so that variety of products can be manufactured on the same equipment.

A key obstacle to the economic application of flexible automation is parts feeding (2.2). Traditionally, dedicated devices such as vibratory bowl feeders have performed parts feeding. Such devices have a high cost, and are dedicated to a single component geometry and, consequently, the number of dedicated feeders required for a planned variety of products is equal to the number of distinct part types. This results in a high capital cost that can only be justified in a dedicated mass production environment, where there are long production runs and few product changes. Dedicated feeding methods are also usually too inflexible for robotic assembly systems where there is a wide range of component types in small batches being produced at lower rates.

2.1 Flexible systems

2.1.1 A new cell production assembly system with human-robot cooperation - 2010

In manufacturing, where the wages of operators are high and the availability of expert operators remains limited, it is proving impossible to improve the efficiency of cell production assembly systems. Even novice operators are asked to achieve high levels of productivity and reliability with a diverse range of products. To satisfy this demand, the authors ([8]) have developed a new cell production assembly system with human-robot cooperation. This system consists of three key technologies; parts feeding by double manipulators on a mobile base, production process information support for the operator, and safety management for cooperation between the operator and the robot. The safety management for the cooperation is new from the viewpoint that industrial robots can cooperate with human operators in automatic operation without stopping, which can achieve higher productivity. The authors demonstrated that, for the assembly of a cable harness, productivity with the new cell can be doubled relative to the conventional manual cell production. Furthermore, the authors proved that the assembly quality with the new cell production method can also be greatly improved because assembly errors can be almost entirely eliminated. In addition, the new method of automatic parts kitting and feeding by the mobile manipulators allows the operators to concentrate on the assembly operations and improve productivity in comparison with conventional manual parts kitting and feeding. This new cell production assembly system is expected to be installed in manufacturing factories in the near future. To promote the installation, the authors will make greater efforts to reduce the cost of the setup including the mobile manipulators and the safety management, and strive to improve safety even further.

2.1.2 Bicriteria robotic operation allocation in a flexible manufacturing cell - 2010

Consider a manufacturing cell of two identical CNC machines and a material handling robot. Identical parts requesting the completion of a number of operations are to be produced in a cyclic scheduling environment through a flow shop type setting. The existing studies in the literature overlook the flexibility of the CNC machines by assuming that both the allocation of the operations to the machines as well as their respective processing times are fixed. Consequently, the provided results may be either suboptimal or valid under unnecessarily limiting assumptions for a flexible manufacturing cell. The allocations of the operations to the two machines and the processing time of an operation on a machine can be changed by altering the machining conditions of that machine such as the speed and the feed rate in a CNC turning machine. Such flexibilities constitute the point of origin of the current study. The allocation of the operations to the machines and the machining conditions of the machines affect the processing times which, in turn, affect the cycle time. On the other hand, the machining conditions also affect the manufacturing cost. This study ([13]) is the first to consider a bicriteria model which determines the allocation of the operations to the machines, the processing times of the operations on the machines, and the robot move sequence that jointly minimize the cycle time and the total manufacturing cost. The authors provide algorithms for the two 1-unit cycles and test their efficiency in terms of the solution quality and the computation time by a wide range of experiments on varying design parameters. The authors have formulated the problem as a Mixed Integer Nonlinear Programming (MINLP) model. the authors developed an exact solution procedure for the S1 cycle. Since the allocation problem for the S2 cycle is NP-Complete, they presented a heuristic algorithm that generates a set of approximate efficient solutions. The authors compared the results of the algorithm with commercial MINLP solvers DICOPT and BARON. The proposed algorithm proved to be very efficient in terms of the number and the quality of the generated solutions and the computational requirements.

2.1.3 An analysis of cyclic scheduling problems in robot centered cells - 2010

The focus of this study ([3]) is a robot centered cell consisting of m computer numerical control (CNC) machines producing identical parts. The existing robotic cell scheduling literature mainly focuses on in-line or mobile robotic cells. In many practical applications, robot centered cells are used simply because they require less space than in-line robotic cell layouts. Furthermore, stationary base robots (as in robot-centered cells) are cheaper to install and easier to program and, consequently, more robust than mobile robots. Two pure cycles are singled out and further investigated as prominent cycles in minimizing the cycle time. It has been shown that these two cycles jointly dominate the rest of the pure cycles for a wide range of processing time values. For the remaining region, the worst case performances of these pure cycles are established. The special case of 3-machines is studied extensively in order to provide further insight for the more general case. The situation where the processing times are controllable is analyzed. The proposed pure cycles also dominate the rest when the cycle time and total manufacturing cost objectives are considered simultaneously from a bicriteria optimization point of view. Moreover, they also dominate all of the pure cycles in in-line robotic cells. Finally, the efficient frontier of the 3-machine case with controllable processing times is depicted as an example. Interestingly, pure cycles are used extensively in metal cutting industry, not because they are provably optimal, but because they are very practical and easy to understand and implement. More specifically, in a pure cycle, each part is loaded and unloaded only once, which means less gaging, one probable reason why this cycle is preferred in practice. Future lines of research directions might be to extend the current study to include multiple part types or dual gripper robots.

2.1.4 Pure cycles in flexible robotic cells - 2009

In this study ([41]), an m-machine robotic cell used for metal cutting operations is considered. The machines used in such manufacturing cells are CNC machines which are highly flexible. As a consequence, each part is assumed to be composed of a number of operations and each machine is assumed to be capable of performing all of the required operations of each part. The authors investigated the productivity gain attained by the additional flexibility introduced by the CNC machines. A new class of robot move cycles, namely the pure cycles, which resulted from the flexibility of the machines are defined. The problem is formulated as a special travelling salesman problem (TSP), where the distance matrix consists of decision variables as well as parameters. Due to the extensive computational effort required to solve this formulation, they determined two specific pure cycles which perform effectively. They determined the regions of optimality for both of these cycles. For the remaining small region, they determined worst case bounds for both of these cycles. They also proved that the set of pure cycles dominates all flowshop-type robot move cycles. The results show that these proposed cycles are not only simple and practical but perform very efficiently as well. As a design problem, they considered the number of machines in a cell as a decision variable and determined the optimal number of machines for the two specific pure cycles. Extending the analysis to the multiple parts case can be considered as a future research direction. In such a case, the determination of the part input sequence must also be tackled which will certainly increase the complexity of the problem even further.

2.1.5 Cooperation of human and machines in assembly lines - 2009

The paper ([15]) gives a survey about forms of human-machine cooperation in assembly and available technologies that support the cooperation. The close cooperation of human and machine in hybrid assembly is motivated by the increased need for flexibility, adaptability and reusability of assembly systems. Hybrid assembly systems can essentially reduce the amount of fixed production costs in relation to variable costs. The effectiveness of these systems depends on the lot size, but also on the design of the cooperative workplace and its automated systems. The overall effectiveness of hybrid assembly also depends on the intelligent feeding of workpieces to the cooperative workplace. An essential precondition for the time efficient close cooperation between human and machine is the safety of the worker. A lot of research has been carried out in this field in recent years and first sensor systems for the surveillance of the interaction between human and robots are available on the market. The research in the field of intelligent assist devices (IAD) that efficiently support the worker is the basis to keep the worker in the loop in order to utilize his cognitive and senso-motoric advantages for highly flexible assembly. The support functions of IADs comprise safety as well as reduction of physical strain and efficient synchronisation between worker and automated systems. Future research will have to focus on different aspects for highly cooperative hybrid assembly. The robustness of the system parts for safety, load reduction and others will have to be increased in order to extend the field of applications. A new challenge will be to improve the cooperation of human and machine not only for a single human but also for a group of workers that have to fulfil a common task supported by one or more machines at the same time. The close cooperation between human and machine may in the future also change the way that automated systems will be programmed. It can be foreseen, that a wide range of automated cinematic systems such as robots will in the future include interfaces for efficient teach modes based on the direct force coupled interaction between human and robot. The human oriented automation approach may generally lead to a change in the design principles for robots. Today design of industrial robots is focused for accuracy. Control with application of external sensors is needed for stable and safe interaction. In long term solutions the design of intrinsically safe robots will focus on safety and sophisticated control will provide accuracy. By this, the next generation of robots will interact with human directly for cooperative manipulation, where the robot is responsible for load-bearing and precision whereas the human can contribute with sensing, intelligence and skills. Generally the advantages of a close cooperation between human and intelligent assist systems in assembly lines build a basis for a more flexible and also more sustainable way of assembly and disassembly in the future.

2.1.6 A market approach to decentralized control of a manufacturing cell - 2009

With manufacturing system evolves from traditional centralized organization to more and more decentralized federation, effective coordination of the resource allocation becomes more and more important. For balancing the influences of various conflicting managerial objectives with an unified instrument in scheduling practice, market approach seems to be an appealing choice. This paper ([6]) introduces a multi-agent framework with bidding mechanism for dynamic scheduling of a CNC manufacturing cell consisting of multiple non-identical workstations. The market model developed is based on a heuristic periodic scheduling procedure the authors proposed. A pricing policy is designed for the effective mutual selection between jobs and workstations. Simulation results show the advantage of theirs proposal over some other approaches. Further observations reveal that as workload arises and job due date tightness increases, the necessity also increases for gathering more jobs arrived over a longer time horizon to get more reasonable resource allocation. This observation gives us some idea on how to select between the policy of periodic bidding and the policy of continuous bidding. Future lines of research directions might be to extend the current study to finding an effective way for the precise determination of the appropriate length of the scheduling horizon T under a certain given workshop configuration.

2.1.7 Modeling of machine failures in a flexible manufacturing cell with two machines served by a robot - 2008

In this study ([38]), a stochastic model is developed to analyze performance measures of a flexible manufacturing cell (FMC) under different operational conditions, including machine failures and repairs. The FMC consists of two machines served by a robot for loading and loading purposes, and a pallet handling system. Stochastic models (Markov processes) and the closed-form solution formulas obtained in this paper could be used to analyze and optimize the productivity and other performance measures of an FMC under different machine, robot and pallet operational characteristics. Using the models presented in this paper, best parameter combinations can be determined for a given FMC system. In particular, best machining rates, robot loading and unloading rates, pallet capacity and pallet transfer rates can be determined for a given set of FMC machine characteristics. Furthermore, reliability and availability analysis of the FMC system can be determined based on different failure/repair characteristics of the machines in the system. It is possible to optimize machine repair rates, based on other system parameters, to achieve maximum production output rates and other performance measures.

2.1.8 Effects of maintenance policies on the productivity of flexible manufacturing cells - 2006

This research ([26]) was undertaken to determine the effects of various maintenance policies on the operational capability (production output rate and availability) of flexible manufacturing cells (FMC). Flexible manufacturing cells are operated at higher usage rates than the traditional equipment since they are flexible and can allow manufacturing of a wide variety of parts. Therefore, they are vulnerable to more wear and tear during their useful life. Maintenance is considered extremely important under such conditions. However, no detailed study can be found in the literature on the effects of maintenance policies on the operational condition of FMC. Five distinct maintenance policies were identified and their effects on production rate, which is a direct outcome of availability, are analyzed by using mathematical formulation of failure rates and simulation modeling. Using SIMAN simulation package, six simulation programs were developed(one for the fully reliable FMC and one for each of the five maintenance policies implemented on the FMC). The results of the analysis of several experiments show that maintenance of any form has significant effect on production output rate or the availability of the FMC. However, the type of maintenance applied is important and should be carefully studied before implementation. The implication of this research is that any FMC system under consideration must be analyzed with respect to several maintenance policies and the best policy should be selected before blindly implementing a policy. As it is seen from the analysis above, the best policy in all cases appears to be opportunity-triggered maintenance policy (OTP) and the worst policy is the corrective maintenance policy (CMP) case, which is operate-to-failure and then repairs case. One important consideration that is not incorporated into the present study is related to the cost aspects. Cost data were not available during the course of this research. Future studies can be carried out on the cost aspects of various policies if such data are available. The best cost saving policy can be determined depending on the specified parameters related to the repair costs and the preventive maintenance costs. In order to perform such a study, one has to collect all maintenance related costs for the system under consideration. Other possible maintenance policies must be studied and compared to those presented in this study. Combinations of several policies are also possible in the same FMC system. For example, while a machine is maintained by one policy, another machine could be maintained by a different policy. These aspects of the problem need further investigation.

2.1.9 Design configuration for a mixed-model assembly system in case of low product demand - 2006

This paper ([17]) addresses the application of a mixed-model assembly balancing problem to an assembly-to-order environment in the case of low production rates and large number of tasks. The aim of this work is to propose an alternative design procedure for the balancing of semi-automated and mixedmodel assembly systems under low product demand effects by the application of multi-turn circular transfers, such as a multi-stations rotating table. This layout configuration permits a job enlargement for human operators and, at the same time, provides an increment in task repeatability through the work-pieces assembling by increasing the number of the turns of the transfer. Finally, the developed heuristic procedure is tested on a simple rotating table assembly cell, a partial representation of a complete assembly system of domestic air compressors.

2.1.10 Dynamic scheduling in flexible assembly system based on timed Petri nets model - 2005

This paper ([24]) investigates a scheduling model for optimal production sequencing in a flexible assembly system. The system features a set of machines working together in the same workspace, with each machine performing a subset of operations. Three constraints are considered: (1) the precedence relation among the operations specified by the assembly tree; (2) working space that limits concurrent operations; and (3) the variation of process time. The objective is to find both a feasible assignment of operations to machines and schedule tasks in order to minimize the completion time for a single product or a batch of products. The assembly process is modeled using timed Petri nets and task scheduling is solved with a dynamic programming algorithm. The method calculates the time required precisely. A detailed case study is discussed to show the effectiveness of the model and algorithm. Future work is required to implement the optimization method with multiple variants to enhance the reliability and robustness of the algorithm. This approach of modeling, planning and control for an FMS will also be further developed.

2.1.11 A stochastic model for the analysis of a two-machine flexible manufacturing cell - 2005

This paper ([11]) presents a stochastic model to determine the performance of a flexible manufacturing cell (FMC) under variable operational conditions, including random machining times, random loading and unloading times, and random pallet transfer times. The FMC under study consists of two machines, pallet handling system, and a loading/unloading robot. After delivering the blanks by the pallet to the cell, the robot loads the first machine followed by the second. Unloading of a part starts with the machine that finishes its part first, followed by the next machine. When the machining of all parts on the pallet is completed, the handling system moves the pallet with finished parts out and brings in a new pallet with blanks. A model with these characteristics turns out to be a Markov chain with a transition matrix of size $5n + 3$, where n is the number of parts on the pallet. In this paper, the authors present exact numerical solutions and economic analysis to evaluate FMC systems, to determine optimal pallet capacity and robot speed that minimize total FMC cost per unit of production. Design engineers and operation managers can benefit from these analysis either during the FMC design phase for the appropriate selection of its components or during its operation phase. The stochastic model of the described FMC can be extended in many directions. A new problem emerges if the number of machines in the FMC is increased to three or more machines instead of two. It will be attractive if the model of this problem turns out to be a Markov chain with an exact solution. Another related problem arises when we assume that each machine is served by a dedicated robot. Although the robot utilization would to be less in this case, it may be interesting to witness the effect on the production rate and machines' utilization and compare them to our model. A further extension is to study and analyze an FMC with unreliable machines and/or robot.

2.1.12 Image based 3D Surveillance for flexible Man-Robot-Cooperation - 2005

In today's industrial production men and robots usually work separately from each other in order to avoid accidents. By this, the advantages of an interoperable automated and manual assembly can not be used for a flexible and efficient production. If it would be possible to overcome the separation of man and robot, the accuracy and speed of robots could be combined with the flexibility and reliability of human workers. Especially for complex assembly and handling tasks, this combination is useful. A system based on digital 3D image analysis has been developed, which supervises the common working area of robot and man. The digital image processing succeeds more and more in replacing conventional safety devices in an automated production. The main advantages are the economical hardware platform and the possibility of a flexible safety area definition. The introduced surveillance technology ([32]) is based on image processing methods for motion analysis, skin colour detection, three-dimensional positioning with a trinocular sensor arrangement and utilisation of human body geometry for defining critical areas. By this it is possible to determine 3D coordinates of humans and machines respectively. The motion areas of men and robot must no longer be partitioned from each other and a safe overlapping operation can take place. Thus the special capability characteristics of humans and machines can be combined in a co-operative work place which complies with the increasing demands for flexible assembly resulting from a more and more individualised production.

2.1.13 A heuristic approach to batching and scheduling a single machine to minimize setup costs - 2004

In this paper ([5]) the authors analyzed the problem of creating batches of jobs and scheduling tools necessary for their processing. This problem arises typically in the management of flexible manufacturing systems. Here, they considered the special case of a single processing facility (e.g. robot) with degree of parallelism $k = 3$, in which no more than k parts may be accommodated in the cell at the same time. In particular, we restricted our research to the case in which exactly $k = 3$ parts are always present in the system.

The objective is the maximization of the productivity of the cell, which corresponds to considering the minimization of the time by which all the jobs are completed (make span). Since the number of batches b is fixed (due to the above assumption), the operations processing times are given and setup times (tools and batches setup times) are independent from the sequence and identical for all the jobs, the objective easily translates into the minimization of the total number of tool setups. Since even for $k = 3$ the problem is shown to be hard (Agnetis et al. 2003), they developed a heuristic solution algorithm, based on LCS concept, that has proved to be effective (in terms of solution values) and efficient (in term of computation times) in practice.

A possible direction for further research, strictly linked to the solution scheme here proposed, is the development of more sophisticated heuristic algorithms (e.g. based on local search meta-heuristic concept such as tabu search or simulated annealing) able to further reduce the optimality gap. A different possibility is the development of approximation algorithms which, differently from heuristic ones, guarantee the solution quality a priori, even in cases when no optimal solution is available.

2.1.14 Framework for designing a flexible cellular assembly system - 2004

The aim of the present paper ([29]) is to develop a conceptual framework for the simultaneous design and control of a flexible, agile reconfigurable and robust assembly system in conjunction with the analysis and optimization of product, process, system structure, material-handling devices and plant layout. An effective solution for reconfigurability and agility in assembly to order and batch-type systems is a modular semi-automatic approach based on cellular flexible facilities: modularity, automation and human skills are combined to gain the advantages of mass production. Families of parts are produced in flexible cells, i.e. groups of various machines and resources that are physically close together and process one or more families of similar parts. The proposed approach is based on a multi-stage iterative procedure that integrates different supporting decision techniques and tools such as design for assembly, group technologies and cellular manufacturing. An application to the optimization of a semi-automatic flexible assembly system is illustrated: the system performances of example alternative solutions are presented and compared.

2.1.15 Mini assembly cell for the assembly of mini-sized planetary gearheads - 2004

This paper ([36]) discusses a novel assembly method and system for a commercially available 8mm diameter miniature planetary gearhead. The system comprises a commercially available four-degree of freedom industrial robot, two vision systems, a force feedback system in the robot wrist, and specially designed flexible part feeders. The system has proved successful in assembling planetary gear units independently. Depending on the task, one can select whether to use the high accuracy and repeatability of the robot or alternatively use programmable frequency vibration in the gripper to stochastically align the parts that the robot handles.

2.1.16 An approach to the design of a manufacturing cell under economic considerations - 2002

In this case study ([4]), a new method to finalize the design of a manufacturing cell aiming for its profit maximization was proposed. The proposed method integrates simulation techniques, design of experiments, regression analysis, Taguchi methods, and a new profit model to facilitate the generation and evaluation of different designs. The application of the method was demonstrated with a case study. The case study included optimal setting of number of associates; raw material inventory policy (frequency, order size, and safety stock); number of machines for a specific operation; and number of setups per planning period. The method was used to generate several designs with high estimated average profit values and low sensitivity to changes in selected non-controllable economical factors. The generation of these designs allowed a DM to choose the best design according to the profit value, robustness, and other practical considerations. The final evaluation of the resulting designs suggested that TM is a viable and simple way to generate a cell design with high profit values and low variability to noise factors. It also became evident that regression analysis can be used to generate a wide span of designs with tradeoffs between them that can be assessed easily with the proposed profit-based method. One advantage of the regression approach is that it produces a number of high-profit designs for the DM to select from while TM produces just one design. In conclusion, the results of this study suggest that the design of a manufacturing cell can be carried out by using potential profitability of the system as the central objective.

Future research

It is recommended that the following ideas be examined in the future:

1. The problem described is not exclusive to manufacturing cells. The proposed method could be used to approach the design of different manufacturing systems;
2. After finishing the full factorial enumeration, the number of alternatives to be chosen for further study is an arbitrary number. It could be researched as to how to determine the number of alternatives that must be selected to raise the probability that the optimal solution is among the selected set;
3. The setting of factors at levels such that the average profit is maximized and the variability around this average is minimized can be found by solving the optimization problem with more efficient means than the total enumeration used here.

2.1.17 Knowledge intensive Petri net framework for concurrent intelligent design of automatic assembly systems - 2001

To effectively carry out the design of assembly systems, an effective approach needs to be developed. However, due to the complexity of design process, various assumptions or simplifications have been introduced in the existing methods to obtain solutions for the problem. The problem using the existing methods to design assembly system is that the unmanageable complexity could occur both in computation cost and storage. The complexity and limitations using the existing methods can be greatly alleviated with the observation as well as idea behind the work reported in this research. This paper ([31]) presented a systematic and concurrent intelligent approach to the modeling, design, and planning of flexible robotic assembly systems. There are two major ideas employed in this approach. One is the use of knowledge Petri net to establish a number of place and transition template. Specific FASs can thus be derived by instantiation from this set of templates. The other is the use of function-behavior-structure model for design and evaluation of FASs. The knowledge Petri net is an enhancement of the conventional Petri nets by employing AI knowledge representation techniques including rule-based technique and frame. It allows the established behavior analysis techniques for Petri nets to be carried out. At the same time, the system complexity can be reduced since any FAS model which built upon a given set of place and transition template can be made more compact. Therefore, the knowledge Petri nets can build a unified, complete framework to represent multiview knowledge and to perform reasoning and learning. Compared to the existing methods, the work essentially has an integrative nature, and the proposed knowledge-based function-behavior-structure design model and framework are more generic. They can be used as an alternative to reduce the computing cost and storage in the design of assembly system. The framework was implemented based on the knowledge Petri net models combined with POSES++ and the conventional procedural language. It has potentials that support all development stages including general design, detailed design, programming, simulation, validation and verification in a consistent and integrated manner. The developed integrated design environment is a 3D modeling, animation, and simulation package, allowing the user to intuitively and interactively build and animate 3D models. The examples show that the approach is feasible, and is an effective means to achieve concurrent design of FASs. The results obtained from this work are generic enough to be applicable for other types of FMS such as flexible machining centers, flexible assembly systems, semiconductor manufacturing systems, etc. However, the work presented in this paper is just a preliminary effort in the automatic assembly system design. A large amount of work to make the proposed approach and system practical use is desired to be done. One of the future efforts will be required to further the research on the mapping from function model to structure for the conceptual design of assembly system. In the meanwhile, the further development of the system is also required.

2.2 Techniques for flexible feeding

2.2.1 Development and testing of a brush feeder - 2010

In this paper ([20]) a brush feeding system based on tilted brushes is presented. It allows the controlled motion and the correct alignment of products different in shape, weight and surface roughness. The brush feeder is analyzed both from a theoretical and experimental point of view. The brush feeder demonstrated good positioning and aligning capabilities both in passive configuration (the chute) and in the active one (vibrating feeder). Several configurations of the feeder have been successfully tested with different components. The paper presents some experimental evidences of the achieved results. The analysis presented here focused on the most influencing parameters, but other parameters and feeder characteristics will be object of future investigations both theoretical and empirical.

2.2.2 Design of a modular feeder for optimal operating performance - 2010

This paper ([18]) presents a design method for a new modular feeder, which ensures an optimal operational behaviour at single or double line frequency through geometric adaptation. The method is based on a structural mechanical model of the system, which was derived from the Lagrangian Equations. Additionally, the best ways for receiving the required model parameters were determined. The model and the adaptation method were verified with a product neutral basic set-up. Occurring deviations were relatively small and therefore can be equalled with an amplitude controller. Finally, the method was included in the design process of the modular feeder, which now has to be tested on industrial applications. Further research should focus on the theoretic determination of the micro-slip effect to avoid the measurement of the leaf spring stiffness.

2.2.3 Approximation to the dynamics of transported parts in a vibratory bowl feeder - 2009

In this paper ([12]) vibration in an electromagnetic drive unit, of the kind typically used for vibratory part feeders, is modelled. The results obtained were used to analyse the dynamic behaviour of a part moving along the spiral track of a vibratory bowl feeder. This analysis led to a series of analytical results covering dynamic, geometric and electromagnetic parameters. What marks this research as different from previous works is the analytical evaluation of the effects of the electromagnetic parameters and associated geometric parameters. The main interest in the results obtained here is the possibility of using analytical results in order to predict part behaviour and select a feeder adapted to particular needs, as well as to optimise the design of a vibratory bowl feeder and its drive unit. As a demonstration of this potential, the authors numerically simulated the effects of certain of the parameters featuring in the expressions that resulted from theirs analysis. Likewise, in order to reinforce the consistency of the numerical results, the behaviour of a part was simulated, using the visual Nastran program, for two different bowl friction coefficients, obtaining results that were entirely congruent. Future lines of research will include a study of the analytical resolution of the complete equation and the verification of these results by real tests.

2.2.4 On-line dimensional measurement of small components on the eyeglasses assembly line - 2008

In this paper ([44]), a novel on-line measuring system for the inspection of small metallic subassemblies for the eye-glasses industry is presented. The automated system proposed is based on artificial vision, and exploits two CCD cameras and an anthropomorphic robot to inspect and manipulate the subcomponents of the eyeglass. Each component is recognized by the first camera in a quite large workspace, picked up by the robot and placed in the small vision field of the second camera which performs the measurement process. Finally, the part is palletized by the robot. The system can be easily taught by the operator by simply placing the template object in the vision field of the measurement camera (for dimensional data acquisition) and hence by instructing the robot via the Teaching Control Pendant within the vision field of the first camera (for pick-up transformation acquisition).The major problem dealt with is that the shape and dimensions of the subassemblies can vary in a quite wide range, but different positioning of the same component can look very similar one to another. For this reason, a specific shape recognition procedure was developed. In the paper, the whole system is presented together with first experimental lab results.

Further testing is currently being performed with the aim of optimizing and expanding the system. Future developments will include the integration of a flexible bulk part feeder in our device, to obtain a completely autonomous inspection system. Another benefit of adding this option will be the possibility of teaching the recognition, measure and manipulation of a reduced number of poses for each subassembly (at least one single pose for each part, possibly the more probable one). In this way, the time required to add a new component to the database will be drastically reduced. During the workcycle, after picking the recognized objects (i.e. the ones which dropped in the taught poses), the objects holding the unknown poses will be flipped by the feeder; finally, a new image of the recognition subsystem will be acquired.

2.2.5 Dynamic modeling and experimental verification of a piezoelectric part feeder in a structure with parallel bimorph beams - 2007

The study ([23]) is aimed to perform dynamic modeling of a part feeder powered by piezoelectric actuation. This part feeder consists mainly of a horizontal platform vibrated by a pair of parallel piezoelectric bimorph beams. It starts with an establishment of the dynamic equations of motion of the piezo-beams in the piezo-feeder via the Rayleigh-Ritz method and is then followed by the modeling on the impact dynamics between the platform and transported part, which is accomplished via basic collision theory. The validity of the established models is further ensured by experiments. The closeness shown between the theoretically-predicted dynamics of the feeder/part and those experimental counterparts finally confirm the success of the modelings. Based on the analytical and experimental results obtained, the following conclusions can be drawn.

1. The first three assumed-modes proposed are capable of predicting the realistic dynamics of a flexurally-vibrated piezoelectric beam, as evident from the experimental results.

2. The basic collision theory is pertinent to be employed to predict the impact dynamics between the platform and transported part, leading to well-predicted part transporting speeds.

3. It is theoretically predicted and experimentally confirmed that the transported part experiences three stages of different types of motions: (1) part arising with the platform; (2) part free falling; and (3) part impacting the platform. This series of interactive three-stage dynamics is repeated between platform oscillation cycles, moving the part from one end to another of the platform. The transported part moves horizontally with the platform in the period of arising with the platform, while it undergoes horizontal motion in a contact velocity in periods of free-falling and collisions.

4. A few general rules for control strategy have been distilled:

    - Based on experimental operation, the feeder should be operated under the resonance frequency of 330 Hz to avoid structural break-down.
    - A basic rule of maximizing the part traveling speed is to increase the input voltage for a shorter period of part stiction to the platform.

Although the part-traveling speeds theoretically predicted in this study anticipate well about the realistics, a broader distribution range of experimental part-traveling speeds as compared to the theoreticals is present. This might be due to the facts that (1) the transported part is not a point mass and (2) the ignorance on the impact friction between the part and platform. To further improve modeling, the part needs to be assumed as a rigid body and one needs to investigate the dynamic effects of the impact friction on the part-transporting speed in the future.

2.2.6 Advanced vision guided robotics provide "future-proof" flexible automation - 2006

Vision guided robotics (VGR) is a fast growing technology and a way to reduce manpower and retain production, especially in countries with high manufacturing overheads and labour costs. The paper ([1]) describes the new automation system of the Swedish company SVIA. Shows that the need to position components to a set pick-up position is eliminated - the vision system determining the position of randomly fed products by a recycling conveyor system. The vision system and control software gives the robot exact coordinates of the components, which are spread out randomly beneath the camera field of vision, enabling the robot arm to move to a selected component and pick from the conveyor belt.

2.2.7 Economic application of piezoelectric actuator in linear vibratory feeding - 2006

The research ([25]) investigated a decoupled vibratory feeding scheme driven by a piezoelectric actuator. In the decoupled design, the action of the horizontal and vertical vibration would be separately controlled to achieve a desired track trajectory and consequently the feed of the part. A computer control method was used to develop voltage input waveforms to control these actuators to produce decoupled movements that cause parts to move forward relative to the track and overcome backsliding and other inefficient feeding motions of conventional operation. To provide a commercial result from research, the authors proposed an economic application of decoupled feeding in an industrial environment, in which a regular PZT bimorph bender is used to drive a linear vibratory feeder in micro-industry. The bimorph actuator is economic and easy to install; however, it needs to be properly controlled to obtain the desired actuation. In the present work, a simple but effective control algorithm was designed to suppress undesired responses of the bimorph actuator, i.e. the disturbance from the harmonic vibration and hysteresis effect. It was noticed that there are many uncertainties inside the acceleration profile during practical feeding; therefore feeding speed cannot be simply calculated, and many factors, such static and motion friction, track flatness, part add in and fall-out, should all be considered further to precisely predict feeding speed. However, it is shown that the control of a decoupled vibratory feeder is feasible and the trend of speed varying based on controlled parameters is clear. Therefore, it is practical and economical to use a commercial PZT actuator in a high-precision-required condition with appropriate control.

2.2.8 A new type of parts feeder driven by bimorph piezo actuator - 2005

A novel meander-line structure implemented with bimorph piezoelectric actuators driven by two sets of alternating current power with phase difference is developed in this article ([9]). Via the generated traveling wave, this mechanism is able to transport parts. The dynamic modeling of the structure, the driving control circuitry design, the motion trajectory analysis and the optimal transport feed rate is studied, and also verified by the practical experiment. The meander-line mechanism is expected to have the advantage of bearing heavier load as compared with the usually seen in-line type of parts feeder with the same size and property of the bimorph actuator. To increase the displacement for better transport efficiency is feasible by changing the size and the property of the bimorph actuator and the connector.

2.2.9 A modular contactless feeder for microparts - 2005

This paper ([7]) describes the development of a feeder for mini and micro parts. A complete study of a feeding method based on electrostatic fields is presented. Through a theoretical analysis and experimental results the optimized configuration of the feeder is proposed, shown and discussed. The performances of possible alternative configurations are quantitatively compared according to the variation of the process parameters. In addition the paper presents a flexible and reconfigurable system based on standard modules easy to be linked by rapid set up operations. A shorter switching period T can increase the feeding rate up to a maximum which is different from part to part: beyond that value parts cannot follow the travelling field. This actual limit of the feeder will be faced in the future development according the principle of parallel feeding through new shapes of the electrodes.

2.2.10 Piezo actuated vibratory feeding with vibration control - 2005

This research ([45]) investigated the effect of decoupling the motion of a conventional vibratory feeder in order to develop a one-axis vibratory sliding mode for feeding tiny delicate parts that could ultimately be adapted to two axes. This research investigated a new type of vibratory drive by employing a piezoelectric actuator. In a decoupled design, the action of the horizontal and vertical vibration would be separately controlled to achieve a desired part trajectory and consequently the feed rate of the part. A computer control scheme was used to develop voltage input waveforms to control these actuators to produce movements that cause the parts to move forward relative to the track and overcome backsliding and other inefficient feeding motions. There are two advantages to this type of design. First, it can handle the parts in a more controlled manner by keeping them in constant contact with the track while maintaining a high conveying speed. This results in good protection for fragile parts. Secondly, this concept results in feedback control schemes that could allow the computer to adjust the drive waveforms to optimize feeder performance. Due to the non-sinusoidal nature of driving waveforms, the higher harmonic components can excite undesired deformation of the responding trajectory. A self-tuning control based on dynamic system identification was employed to counteract the higher harmonic effect. A one-dimensional hardware model is built and experiments were conducted to verify the precision and feasibility of the controlled actuation. The results are promising for industrial applications of decoupled vibratory parts feeding using piezo-electric actuators.

2.2.11 Development of a flexible and programmable parts feeding system - 2005

This paper ([21]) describes the development of a flexible and programmable vibratory bowl feeding system which is suitable for use in a flexible manufacturing system. Controlled by computer and driven by electro-pneumatic cylinders and stepper motors, this feeding system is capable of identifying the orientations of on-rotational parts and actively re-orientating them into the desired orientation. A neural network is incorporated into the system to identify the orientation of parts moving on the track of the vibratory bowl. The neural network obtains scanned signature of the surface of the parts and compares them with learned patterns. With the use of optical sensors, internal features such as holes and pockets can be detected. Three types of neural network architectures (ARTMAP, ART2 and Back-propagation) were evaluated for their capability in pattern recognition and classification of the feed orientation of parts in the vibratory bowl. ARTMAP was found to yield the best results. The system developed extends the capability of conventional bowl feeders to include feeding parts with only internal features, and feeding a family of similar parts without costly re-tooling. These features are well suited to applications in flexible manufacturing systems.

2.2.12 Modal analysis and control of a bowl parts feeder activated by piezoceramic actuators - 2004

Vibratory bowl feeders are the most versatile and common feeding and orientating devices for automatic assembly. Thus, they are being widely used in many industry fields. The electromagnet has been and being commonly used as an exciting actuator in these vibratory bowl feeders. However, because of complexity of its mechanical structure and limited capability, there exist various impending problems such as severe noise, non-linear motion of parts, passive characteristics and so forth. Despite of many research works to improve dynamic performance of the conventional electromagnet actuator-based bowl parts feeder, there still exists some significant problems; noise and passive motion. As one of solutions to resolve these problems is to use piezoactuators as a new exciting technology. The piezoelectric material is one of smart materials that can develop mechanical strain when subjected to an electric field, or, alternatively can develop an electric field subjected to mechanical deformation. Advantages of the piezoelectric material include fast response time, wide frequency bandwidth and accurate control capability. By adopting the piezoelectric material as an exciting actuator, we can devise more effective bowl parts feeder providing accurate and adjustable feeding speed of parts than the conventional one activated by the electromagnet actuator. In this work ([37]), as the first phase to develop highly effective piezoactuator-driven bowl parts feeder, a system model is established using a finite element method (FEM). By adopting commercial software package, modal characteristics of the proposed bowl parts feeder are analyzed and compared with experimentally measured ones. In addition, control aspects of the parts feeder are experimentally investigated by emphasizing the feeding speed of parts with respect to the intensity of the input voltage. The results presented in this research work are quite self explanatory justifying that the bowl parts feeder activated by the piezoceramic actuators can be effectively used in the automatic assembly line. It is finally remarked that optimal adaptability of the proposed parts feeder to various types of parts and noise reduction during excitation have to be further investigated in the future.

2.2.13 Simulation software for parts feeding in a vibratory bowl feeder - 2003

This paper ([46]) describes the development of three-dimensional (3D) computer simulation software to simulate parts feeding and orienting in a vibratory bowl feeder. A mathematical model of part motion and the interaction of the part with the orienting mechanism were developed. Based on the mathematical model, a 3D simulation software has been developed using Java. The key technology involves 3D object modelling and collision detection, which were developed with

Java 3D API. The simulation software can perform dynamic simulation of part motion and the interaction of simple parts with the designed orienting mechanism, therefore enabling the reliability and capability of the design to be assessed prior to fabrication. The computer simulation was verified by carrying out physical experiments in the laboratory. Good agreement between the results of the computer simulation and experiments was obtained. The software can perform simulation to evaluate the performance of part interaction with the orienting mechanism, which was designed by the user, and the designer can then use the design information which is saved in the resource file by the software to generate engineering drawings for fabrication.

2.2.14 Using air streams for part feeding systems - innovative and reliable solutions for orientation and transport - 2003

This paper ([49]) describes the development of innovative feeding technologies based on aerodynamic effects. The general idea of aerodynamic part feeding is to create, e.g. a permanent air field which forces the part into the desired orientation without the need for any control by sensors. An exclusively aerodynamic system offers the highest potential for achieving the goals of high process-speed and inherently flexible feeding. The prototype implementation show how easily and reliably such systems can be applied, although special aerodynamic knowledge is necessary. Further investigations of the IFA will be made to what kind of workpieces and assembly systems are suitable for aerodynamic feeding.

2.2.15 Mechatronic design of a flexible vibratory feeding system - 2003

This paper ([35]) describes the development of a sensor-based flexible vibratory feeding system (SBFVFS) for agile manufacturing, which when fully developed will consist of a decoupled vibratory feeder, a machine vision system, displacement sensors, power amplifiers and a computer system. Its major feeding parameters such as the vibration angle, frequency, acceleration amplitude and phase difference can all be easily adjusted online by software means. Consequently, the system can not only feed a wide range of parts without any retooling of the feeder but can also feed various parts made of different materials in a way close to the optimal state. The SBFVFS also has some built-in intelligence. It can find out the natural frequencies of the decoupled vibratory feeder by means of an automatic frequency response analysis and hence determine the best frequency for the driving signals. It can also find out by machine inspection whether any parts are jamming and eliminate them by making the parts move in reverse directions. A prototype of the SBFVFS has been successfully developed. Experimental investigation is carried out based on the prototype and the results are promising.

2.2.16 Chaotic dynamics of repeated impacts in vibratory bowl feeders - 2002

The dynamic behavior of a single part on the vibrating track of the bowl feeder has been modelled and analyzed ([14]). The numerical simulation and experimental results for dynamic behavior and conveying rate in both periodic and chaotic regimes are presented. The dynamic effects from the variation of several physical parameters are examined and the important features for the effective design of the vibratory feeder are presented. While most of the previous studies were restricted to the purely periodic regime, the existence of chaotic regimes is pointed out numerically and experimentally in this paper. The periodic and chaotic region in hopping regime is identified through experiments and the feed rates in each region were compared to numerical simulation results. It was verified experimentally that the conveying rate in the chaotic regime is more or less independent of variations of the external parameters such as control parameter and load. The results of experiments confirm the trends of numerical analysis for the feed rate. Therefore, the simplified model and accompanying numerical analysis method can be used as an effective design tool for vibratory feeders. This research holds much potential for leverage over design problems of a wide range of mechanisms and tools with repeated collisions.

2.2.17 Generic flexible assembly system design - 2002

The development of a generic flexible assembly system involves the design, selection and integration of a number of different mechanical systems in order to develop an assembly system, which is capable of assembling a wide variety of products having an unknown specification. A specific system configuration being dependent on a variety of factors such as, product size, weight, component insertion direction, and manipulator geometry. This paper ([30]) examines each of the factors that should be considered when designing a generic flexible assembly system and presents a novel generic flexible assembly system design.

2.2.18 Orienting polyhedral parts by pushing - 2002

A common task in automated manufacturing processes is to orient parts prior to assembly. The authors consider ([43]) sensorless orientation of an asymmetric polyhedral part by a sequence of push actions, and show that is it possible to move any such part from an unknown initial orientation into a known final orientation if these actions are performed by a jaw consisting of two orthogonal planes. They also show how to compute an orienting sequence of push actions. The authors propose a three-dimensional generalization of conveyor belts with fences consisting of a sequence of tilted plates with curved tips; each of the plates contains a sequence of fences. We show that it is possible to compute a set-up of plates and fences for any given asymmetric polyhedral part such that the part gets oriented on its descent along plates and fences.

2.2.19 Development of a model for part reorientation in vibratory bowl feeders with active air jet tooling - 2001

Vibratory bowl feeders (VBFs) are widely used in industry for feeding and reorienting small parts in high volume production. This research ([22]) describes the development of a model of part behavior required for reorienting a part with an air-jet-based computer controlled orienting system. The control algorithm accepts the part's weight, geometry, and its orientation. Sensors then compare the present with the desired orientation and the algorithm determines the appropriate pulse of air to produce the desired orientation. The model was validated experimentally for a specific part. This model can be used to reorient parts and improve feed rates in sensor-based active air jet vibratory bowl feeder systems.

2.2.20 Flexible parts feeding for flexible assembly - 2001

This paper ([28]) describes a compact, low cost belt feeder prototype based on Pherson et al.'s (1983) concept but, which is capable of feeding complex geometries using modern sensor technology for part recognition, a standard non-active orientation blade, and a novel method for handling cylindrical parts.

Limitations

As with all part feeding systems, the belt feeder described in this paper has limitations; components need to have at least one non-rolling stable orientation; they need to be physically robust enough to circulate in the feeder; they must not be transparent. There are also component size limitations: with the current pusher dimensions, components less than 12 mm in length and greater than 50 mm wide are difficult to separate. Components less than 1 mm thick cannot be fed because they jam under the belt guides. The feedrate is limited by the velocity of the conveyor belts and the likelihood of a correct part orientation.

Conclusions

- A flex-feeder based on the double belt feeder concept is potentially economic and versatile. It is possible to build a compact low-cost flex-feeder having an equivalent cost to a vibration bowl (£7000 to £9000). The prototype flex-feeder was constructed for £5600.
- Vision system technology has developed enough to overcome the limitations of the early flex-feeders.

- The double belt feeder described in this paper is more compact and cheaper than other commercially available flexible feeding systems.
- The prototype flex-feeder would be an ideal replacement for a vibratory bowl feeder where parts are subject to wide tolerance variation, e.g. distortion in plastic parts or there is a requirement to feed many different parts in the same feeder.
- A low-cost pattern matching sensor can be used to identify part orientations, but is limited to parts that do not tangle or nest.

Further work

- A more advanced vision system will be used to simplify, and speed the set-up operation between part changes.
- Three different sizes of belt feeder are proposed to cater for different component sizes.
- The effect of the step height between the return and feed belt will be studied.

2.2.21 New Feeding System for High Speed Assembly of Small Parts - 2000

This paper ([39]) presents the new general purpose automatic feeding system, developed for high speed assembly of small parts. The new design is a result of the consequently applied Axiomatic Design Theory. The feeding system is functionally uncoupled, leading to minimization of problems in system tuning, parts damage and noise emission. Moreover, the new design gives the possibility for simple introduction of additional functional modules such as: sensorized modules for non-geometrical orientation of parts, or active orientation modules for improving efficiency of the system. The proposed system is verified by the prototype developed for feeding screws on pneumatic screwdriving station. Future research will address more strictly in the mathematical formulation of the proposed methodology, as well as the improvement of already developed feeding system.

2.2.22 Designing a parts feeding system for maximum flexibility - 1997

Short-run production, frequent product modifications, and pressures to reduce product time to market make flexible manufacturing increasingly desirable. Despite advances in flexible systems, the problem of feeding parts to an assembly line is not fully addressed by conventional methods such as bowl feeders.

New technologies ([16]) such as Intelligent Automation Systems’ FPF2000 Flexible Feeder for Small Parts offer additional versatility for short production cycles with frequent changes, and multiple simultaneous assembly lines.

Capitolo 3

THE ARTICLE SELECTED

IN THIS CHAPTER we present the papers of J. Krüger, T.K. Lien, A. Verl (2009) and M. Morioka, S. Sakakibara (2010).

3.1 Cooperation of human and machines in assembly lines

Flexibility and changeability of assembly processes require a close cooperation between the worker and the automated assembly system. The interaction between human and robots improves the efficiency of individual complex assembly processes, particularly when a robot serves as an intelligent assistant. The paper gives a survey about forms of human-machine cooperation in assembly and available technologies that support the cooperation. Organizational and economic aspects of cooperative assembly including efficient component supply and logistics are also discussed.

3.1.1 Introduction

Skilled robotic systems are key components in fully automated assembly processes as a part of a highly efficient production. Due to smaller lot sizes of customized products the demands for increased flexibility and adaptability to changing assembly tasks are rising continuously. Therefore a robot assisted but human guided assembly has various significant advantages compared to full automation (Bley H, Reinhhart G, Seliger G, Bernardi M, Korne T, 2005).

Flexibility and changeability of assembly processes require a close linkage between the worker and the automated assembly system. The interaction between human and robot improves complex assembly processes, particularly when a robot can be guided by a worker and the robot provides power assistance to the worker.

Various forms of support can be provided to the worker in manufacturing processes, depending on the degree of assistance with sensors, actuators or data processing (Fig. 3.1). For assembly processes robot assistance combines these components in order to give support for difficult, monotonous or exhausting tasks.

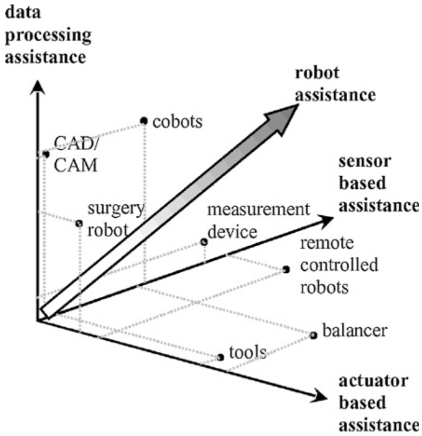


Figura 3.1: Influence factors on robot assistance (www.assistor.de).

3.1.2 Human-machine cooperation in assembly lines - state of the art

3.1.2.1 Hybrid assembly

The close linkage of human and machine in cooperative assembly tasks should make use of the strengths of both sides. Typically an automated assembly system provides a couple of advantages such as operation without breaks and fatigue and high productivity for simple assembly tasks. Though, flexibility of automated systems such as robots normally is restricted due to high programming effort and limited abilities for handling of complex or limp parts.

On the other hand a human provides incomparable sensomotoric abilities for complex handling tasks, can quickly adapt to new process sequences but is restricted in force and precision. Cooperative work stations combine the advantages of a human and an automated system (Fig. 3.2).

One way of utilizing robotic and human capabilities at their best is obtained in assembly system where there is a sequential division of tasks. The simple tasks suited for robots are found upstream in the line. The complex frequently varied tasks that give the assembled products their individual features are performed downstream by human operators. Such hybrid lines have been used to advantage in industry for more than two decades (Lien TK, Rasch FO 2001).

Today, especially for the assembly of heavy or bulky parts, weight compensators/balancers are used. Since these systems do not compensate for inertial

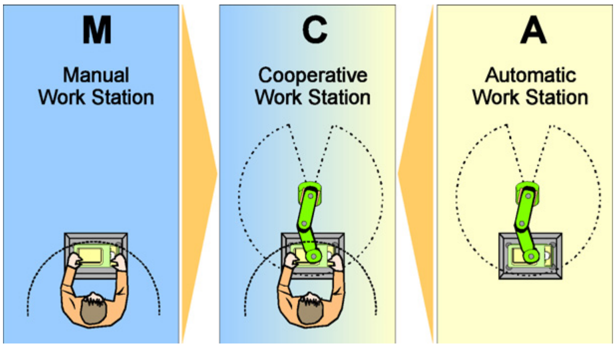


Figura 3.2: Combination of a manual and an automatic work station (Krüger J, Bernhar, dt R, Surdilovic D, Seliger G 2006).

forces, even small mistakes lead to work-related injuries (lower back pain, spine injuries) (Zaeh MF, Prasch M, 2007). According to statistics of the Occupational Safety & Health Department (OSHA) of the US Department of Labour[1], more than 30% of European manufacturing workers are affected by lower back pain which brings with it enormous social and economic costs. In order to improve this situation, a careful design of socalled intelligent assist systems (IAS) or intelligent automation devices (IAD) and their operating procedures is necessary when physical collaboration between machines and human workers also have to follow ergonomic targets. Fig. 3.3 shows an IAD for cockpit assembly.

Figura 3.3: Cockpit install with IAD (www.stanleyassembly.com).

Industrial applications of human-machine cooperation are mainly to be found in automotive industry. Stanley Automation (www.stanleyassembly.com) provides IADs, which support the worker in assembly tasks such as

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[1] www.osha.eu.int

- axle sequencing,
- cardboard blank handling,
- catalytic converter test cell,
- engine block handling,
- floor pan transfer,
- front sub-frame transfer,
- instrument panel load,
- strut handling,
- transmission handling,
- transmission sequencing.

This IAD technology was originally developed by the US company Cobotics in 2003 and is based on fundamental research done by Colgate and Peshkin (1996). Further research for so-called power amplifying assist devices (IPAD) was done by Fraunhofer IPK (Krüger J et al 2006) Fig. 3.4.

Figura 3.4: IPAD - a reliable approach for advanced material handling (Krüger J et al. 2006).

Hybrid assembly systems can be divided into two groups:

- workplace sharing systems,
- workplace and time sharing systems.

3.1.2.2 Workplace sharing systems

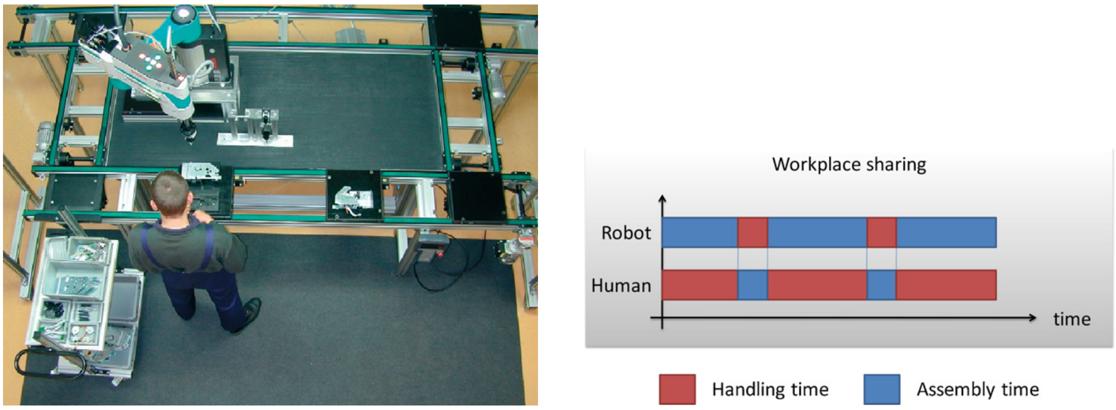
In workplace sharing systems robots and human beings are both working in the same workplace, and both are performing handling tasks as well as assembly tasks in two different configurations:

- Either the robot is performing an assembly task and the human worker is performing a handling task,
- or the robot is performing a handling task and the human worker is performing an assembly task.

The interaction of the robot and the human worker is limited to the avoidance of collisions; the robot will stop if the distance between robot and human being is below a given security distance.

Fig. 3.5a shows an example of a workplace sharing hybrid system: the team@work system of Fraunhofer IPA and IPK (Thiemermann S, Schraft RD 2003). In this scenario several components have to be assembled on a sheet metal part which is supplied by a conveyor system. The human worker has to grip the components out of bins, in order to transport these parts towards the conveyor system (handling time) and to put the components on the sheet metal parts (assembly). Afterwards, the robot has to screw these components into the sheet metal part (assembly). If the worker is too slow, the robot will wait until the worker has finished his tasks.

The task distribution between robot and human worker in this scenario is as follows (Fig. 3.5b).



(a) *Example.* (b) *Time distribution between human and robot.*

Figura 3.5: Workplace sharing systems.

3.1.2.3 Workplace and time sharing systems

In workplace and time sharing systems the human worker and robot are additionally able to jointly perform a handling task or an assembly task at the same time, i.e. there are four different configurations:

- the robot is performing an assembly task and the human worker is performing a handling task,
- the robot is performing a handling task and the human worker is performing an assembly task,
- the robot and the human worker are jointly performing a handling task,
- the robot and the human worker are jointly performing an assembly task.

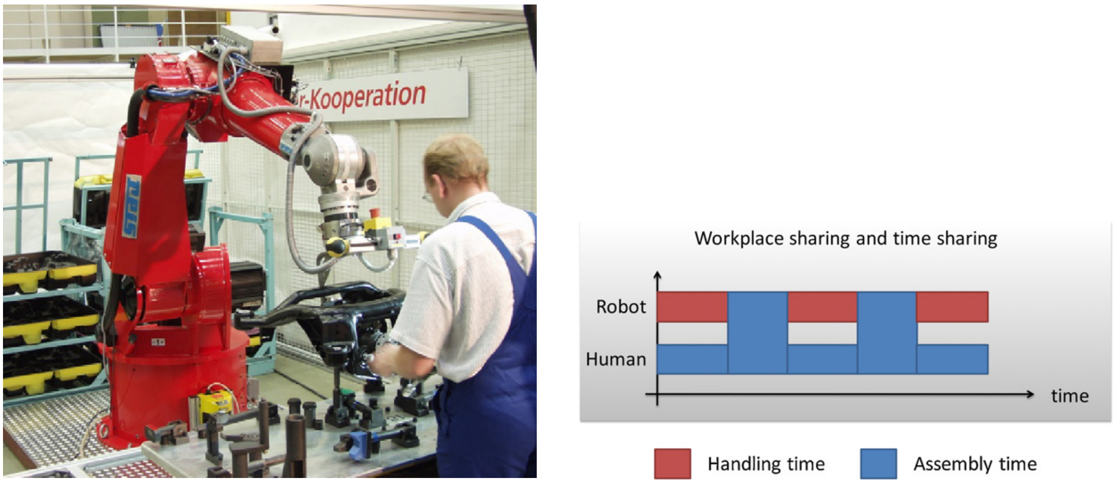
In order to jointly handle or assemble objects the robot has to interact with the human worker on a level which is much higher than just the avoidance of collision.

In the scenario which is shown in Fig. 3.6a, the PowerMate system of Fraunhofer IPA (Schraft RD, Meyer C, Parlitz C, Helms E, 2005), the interaction between robot and human worker is realized with a force-torque-sensor which enables that the robot can be moved by the human operator.

The task of this hybrid system is to assemble heavy parts of an automotive rear axle. In order to do this, the robot has to grip part A out of a box and has to move it to the human worker. As these movements take place in an area where the human operator has no access the robot is allowed to move at maximum speed. As soon as this part is in the shared workspace the robot stops and changes to a cooperation mode. In this cooperation mode the human worker is able to move the robot by pushing, pulling or turning a special handling device which is mounted at the robot gripper in combination with a force-torque-sensor.

In this cooperation mode the human operator is able to ensure a very precise positioning of part A, so that part A can easily be assembled with part B. As soon as this task is done, the robot moves part AB to a second bin and moves back to the first bin in order to pick part A′ . In between the human operator prepares part B′ which will be assembly with part A′ in the next cycle.

The task distribution between robot and human worker in this scenario is as follows (Fig. 3.6b).



(a) *Example.*

(b) *Time distribution between human and robot.*

Figura 3.6: Workplace and time sharing hybrid system.

In this scenario the robot serves like an intelligent and powerful tool to the human operator. The research project PISA deals with flexible assembly systems through workplace sharing and time sharing human-machine cooperation (Bernhardt R, Surdilovic D, Katschinski V, Schröer K,2007). The focus of the project is on novel intelligent assist systems, planning tools for their integration as well as reconfigurability and reusability of assembly equipment. The overall goal is to keep human workers in the loop but to support them with powerful tools. With respect to the design of a sustainable production several criteria can be improved using human-robot interaction in assembly.

3.1.3 Technologies for cooperative assembly

3.1.3.1 Interfaces between human and machines

For the efficient cooperation and interaction the human-machine-interface has an essential role. Interfaces for hybrid assembly systems can be divided into two classes:

- remote interfaces such as visual interfaces, interfaces for gestures (Asfour T, Berns K, Dillmann R, 2000) and voice and
- physical interfaces such as haptic interfaces, displays and head mounted displays (HMDs) as well as force feedback systems.

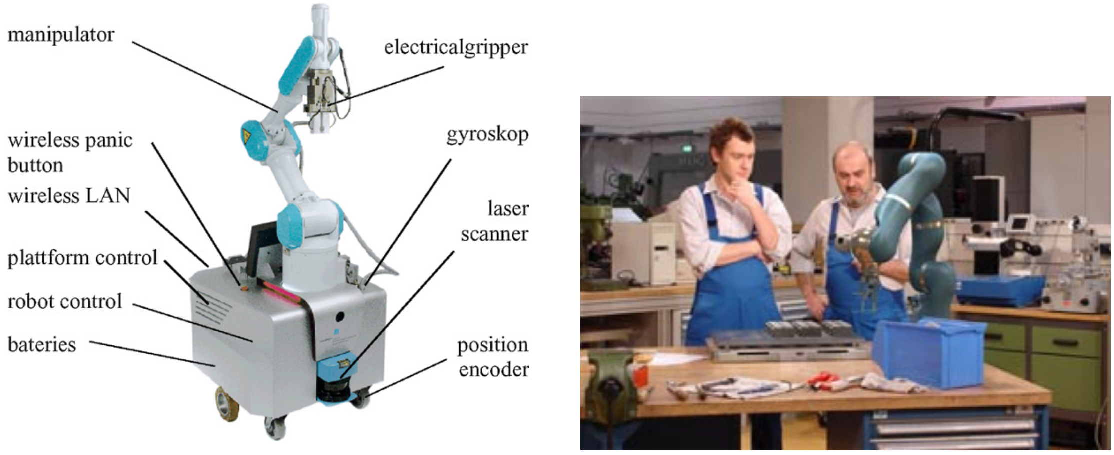
Robotic systems are typically operated via teach panels or graphical user interfaces. An intuitive way of commanding a mobile robot assistant can be achieved by verbal or gesture commands (Ehrenmann M, Lütticke T, Dillmann R, 2001, Ehrenmann M, Becher R, Giesler B, et al, 2002, Theis C, Iossifidis I, Steinhage A, 2001). Due to environmental noise in assembly lines voice control of a robot may be problematic whereas guidance by gestures may provide a robust form of communication between human and robot for short range remote control. The disadvantage of the use of voice or gesture is the single direction control providing only visual feedback of robot motion. For many types of assembly tasks a closer interaction between human and robot is needed, which includes a direct physical contact between both. Socalled admittance displays provide force feedback enabling the operator to feel the contact between robot and assembly target by rendering the contact impedance of the robot environment to the human (Krüger J, Bernhardt R, Surdilovic D, Seliger G, 2006, Colgate JE, Wannasuphoprasit W, Peshkin M, 1996).

3.1.3.2 Robotics

Assist robots

Helms et al. (2002) define a robot assistant as a direct interacting, flexible device, that provides sensor based, actuator based and data processing assistance.

The assist robot rob@work was designed by the Fraunhofer Institute IPA. It is a complex mechatronic system consisting of a mobile platform with differential gear drive, energy supply for 9 h of work and a control system. Different tools such as welding devices or drilling machines can be plugged to the seven DOF manipulator. Target applications for rob@work are to be seen in small series and lot size one manufacturing as well as in maintenance tasks (Fig. 3.7a).



(a) *Hardware architecture of rob@work (Schraft RD, Helms E, Hans M, Thiemermann S, 2004).*

(b) *Robotic assist system.*

Figura 3.7: Assist robot.

The SME$robot^{TM}$ initiative (www.smerobot.org) offers an escape out of the automation trap through:

- Technology development robot systems for small and medium enterprises (SME) adaptable to varying degrees of automation, at a third of today's automation life-cycle costs,
- new business models creating options for financing and operating robot automation given uncertainties in product volumes and life-times and to varying workforce qualification,
- empowering the supply chain of robot automation by focusing on the needs and culture of SME manufacturing with regard to planning, operation and maintenance.

An example of a robot assist system realized in the SME$robot^{TM}$ initiative shows Fig. 3.7b.

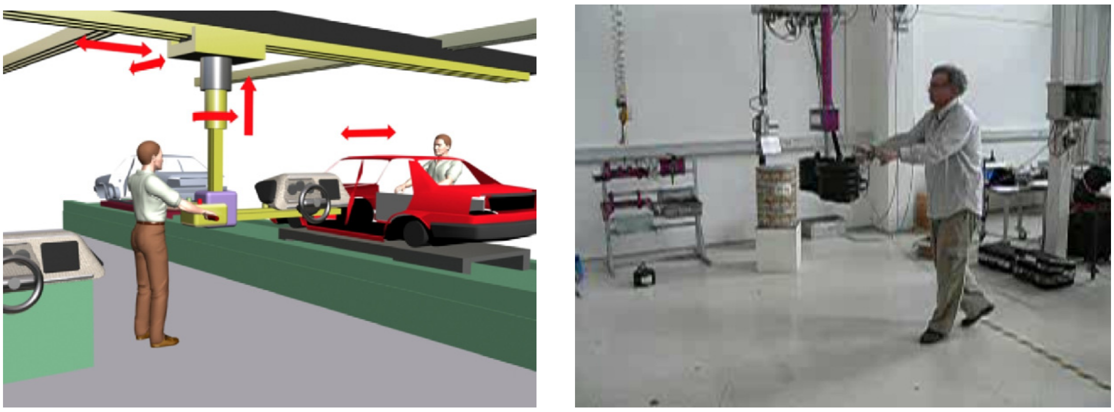
Issofidis et al. (2002) introduced an anthropomorphic robot assistant for human environment based on a seven degree of freedom (DOF) manipulator arm in combination with a two DOF stereo camera head. The robotic system comprises an interface to the worker for the interactive correction of grasping orientation of the end effector.

Collaborative robots (COBOTS)

Collaborative robots or cobots invented by Edward Colgate (Colgate JE et al.

1996, Akella M et al. 1998) are mechanical devices that provide guidance through the use of servomotors, while a human operator provides motive power. Cobots can provide a virtual surface used to constrain and guide the workers motion.

Another important difference of Cobots compared with simple balancers is the ability to provide power support to the worker in a way that apparent inertia of heavy work pieces can be reduced by a factor ten or more, which means that physical strain of the worker during handling of large work pieces is reduced significantly (Figs. 3.8a and 3.8b).



(a) *Rail crane based cobot concept for assembly (Krüger J et al. 2006).*

(b) *Rail crane based cobotic system providing power supply in order to reduce apparent inertia of heavy workpieces (Surdilovic D et al. 2005, 2007).*

Figura 3.8: Cobots.

For the support of the worker during handling tasks with heavy loads exoskeleton systems represent an alternative approach. Due to the tight coupling between the robotic axis the force control of the robotic system is complex (Kazerooni H, 1995). Compared with collaborative robots the exoskeleton systems provide a higher degree of mobility but on the other hand adaptation to the human body is time-consuming.

Direct interaction between human and robot is also applied in surgery. In these applications dynamic constraints are applied in order to control the authorized motions of the surgical tool held by the human operator during a planned task (Delnondedieu Y, Trocazz J, 1995).

Robustness and stability of human-robot interaction

The most popular method of controlling physical human-robot interaction is to vary the robots end point impedance by appropriate control strategies. Thereby an implementation of haptic displays is possible by displaying varying impedances / admittances at the interaction point of human and robot.

Guaranteeing robust stability turned out to be a crucial challenge of such interactive systems. Therefore the coupled stability of interactive robots has been a subject of intensive research in the past 25 years.

A variety of frameworks for coupled stability of interactive robots have been developed but especially when interacting with unpredictable environments like a human problems remain with these frameworks.

Hogan and Colgate (1988) proposed a controller design framework using passivity of the controlled robot as a design criterion. For long years this was the major method for designing interactive controllers and a variety of advanced methods were developed on this foundation. One of those advanced method is natural admittance control (NAC) (Dohring M, Newman W, 2003).

Hannaford (1998, 1999) derived a two-port framework to describe the interaction of users with virtual environments via haptic interfaces. Using this framework he describes stable haptic interaction using passivity criteria.

For handling heavy objects comparatively stiff and heavy robots are needed. The performance of a haptic interface to such a robot based on above mentioned methods is very limited. Several research groups (Buerger SP, Hogan N, 2006, Sugano S, 2000) have derived methods of improving performance in high force haptics using environment models and a robust control framework (Colgate et al. 1989, Vukobratović M et al.2002, Book W et al. 1996).

Interactive learning of assist robot

Fig. 3.9a shows a robot system, for which interactive control by the worker is realized through pointing to objects with laser pointers. Within the SME Robot Project (www.smerobot.org) technology for simplified teaching the robot by guidance was developed based on force-torque-sensors (Fig. 3.9b).

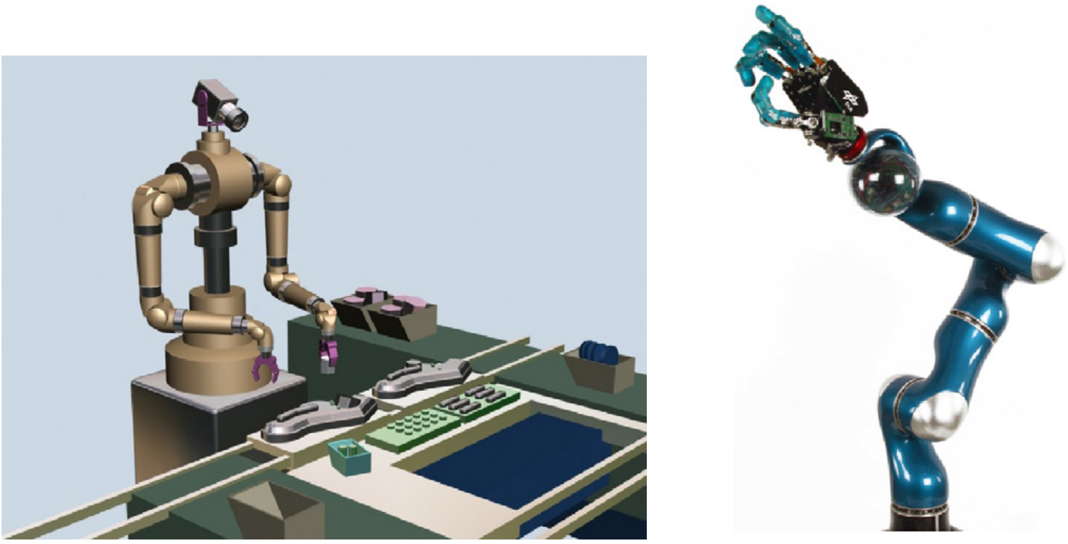
(a) *The worker is pointing out objects directly in the scene using a laser pointer (Stopp A, Horstmann S, Kristensen S, Lohnert F, 2003).*

(b) *Teaching the robot by manual guidance using force-torque-sensors.*

Figura 3.9: Robot system.

Humanoid/anthropomorphic robotic systems

A future flexible assembly line will incorporate different workplace types varying from fully automated work cells to manual assembly places. Between these extremes different types of cooperation and interaction between human and robot are applied to achieve maximum flexibility. For this purpose a humanoid two-arm manipulation robot which can perform complex tasks can work at a human's workplace (Fig. 3.10a).



(a) *Humanoid portable robot for flexible assembly (Bernhardt R et al. 2008).*

(b) *Humanoid light weight robot structure (Albu-Schäffer A et al. 2007).*

Figura 3.10: Humanoid/anthropomorphic robotic.

Besides the humanoid construction the major difference of the robot arm shown in Fig. 3.10b compared to industrial robots is its light weight structure providing intrinsic safety.

The Deutsches Zentrum für Luft-und Raumfahrt (DLR) designed humanoid robots for application areas which are generally not covered by industrial robots, but are still ongoing research topics.

Typical examples are:

- Assembly processes for which the position estimation for the mating parts and/or the positioning accuracy of the robot is significantly below the assembly tolerance,
- applications in which the robot works in immediate vicinity of humans and possibly in direct physical cooperation with them,

- mobile service robotics applications (arms mounted on mobile platforms), for which the information about the position of the robot and the surrounding objects, as well as about the dimension of these objects is afflicted with relatively high uncertainty (Albu-Schäffer A et al. 2007).

Portable robots

The workspace of portable assist systems is not restricted to the place of its actual use but can be chosen within the production environment. This innovation comprises a couple of advantages for manufacturing and assembly:

- Due to a parallel task operation of man and machine, efficiency can be increased,
- cost reduction and improvement of ergonomics is achieved by use of the specific strengths of human and machine,
- flexibility and adaptability with respect to place of installation of handling technology, capacity, experience and knowledge of staff and also with respect to type and complexity of the assembly task can be improved (www.assistor.de).

In order to improve the flexibility of industrial robots for material handling, a portable robot system has been developed by Brecher et al. (2005) within the project PORTHOS.

The robot system can be installed at machine tools for feeding of workpieces (Fig. 3.11).

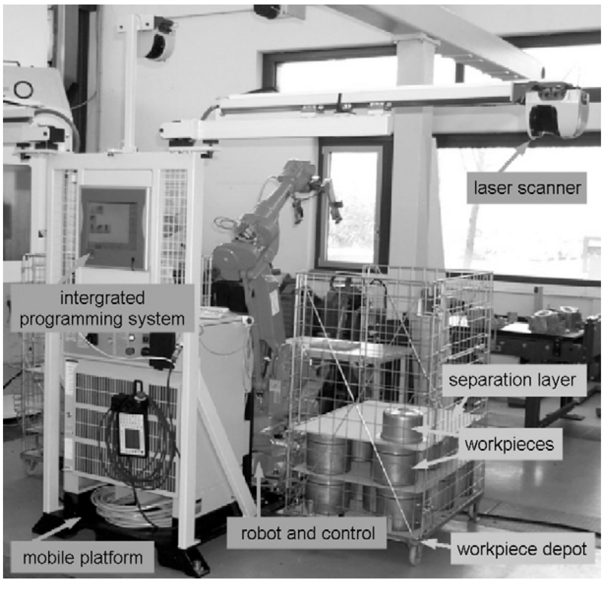


Figura 3.11: Setup of the PORTHOS robot system (Brecher et al. 2005).

For the generation of robot programs a programming system is introduced that combines the traditional approaches of online-and offline-programming in order to allow fast and easy reprogramming of material handling tasks. The main feature of the programming system is an intuitive user-interface that can be operated without special qualifications.

3.1.3.3 Sensors and actuators

Besides advanced control strategies to achieve a compliant and thereby safe robot behaviour a second approach favours the use of inherently compliant actuators to guarantee safety during human-robot interaction (Som F, 2006, Zinn M, Khatib O, Roth B, 2004).

The main design goals of the DLR lightweight robots (Fig. 3.12) were to build a manipulator with kinematic redundancy similar to the human arm, i.e. with seven degrees of freedom (DOF), a load-to-weight ratio of approximately 1:1 where industrial robots typically have a ratio of 1:10 or lower, a total system weight of less than 15 kg for arms with a work space of up to 1.5 m, and a high dynamic performance. There should be no bulky wiring on the robot and no electronics cabinet as usually required by typical industrial robots.

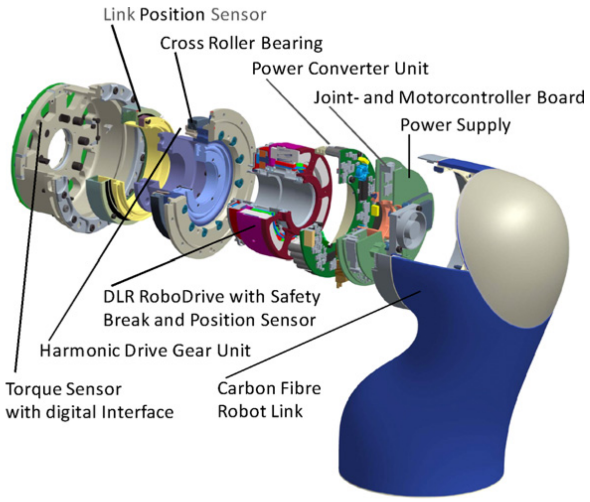


Figura 3.12: The mechatronic joint design of the LWR including actuation, electronics, and sensing (Albu-Schäffer A et al. 2007).

The full state measurement in all joints is performed in a 3 kHz cycle, using

- strain gauge-based torque-sensing,
- motor position sensing based on magneto-resistive encoders, and
- link-side position sensing based on potentiometers (used only as redundant sensors for safety considerations).

3.1.3.4 Safety systems

The desired coexistence of robotic systems and humans in the same physical domain, by sharing the same workspace and cooperating in a physical manner, poses the very fundamental problem of ensuring safety for the user and the robot.

The European norm "DIN EN 775 Safety of manipulating robots" which is right now revised and converted into the international standard "ISO 10218: Robots for industrial environments - Safety requirements" forms the current basis for safety in a robot cell. Already with the implementation of the DIN EN 775 the possible installation of a robot system within reach of a human was considered under highest security conditions. One of the targets of the ISO 10218 now is to further provide regulations for the robot-human-cooperation (Oberer S, Schraft R-D, 2007). Fig. 3.13 shows the safety-related steps from classical robot cells to human-robot interaction.

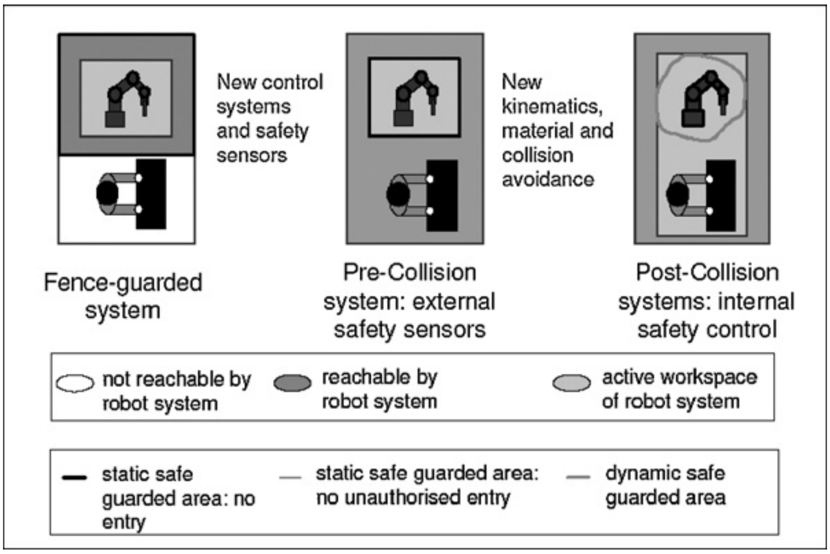


Figura 3.13: Safety control - from the classical robot cell to human-robot interaction.

Pre-collision systems

Control based limitations and sensor based surveillance of the workspace

REIS-Robotics introduced a control feature for their robot systems, with which flexibly programmable limitations for automatic operation can be defined. The robot arm exclusively moves within these restricted areas (Fig. 3.14). These regions can be programmed by direct teach-in, which means in a haptic way by use of a 6-DOF-sensor at the end effector, or in a classical way by teach-in panel or offline-programming/robot simulation system.

The changing characteristics of robot processes, with increasing payloads, work ranges and cycle times necessitate a more flexible approach to safety, which

Figura 3.14: Safety controller for robot assisted welding (Kroth E, 2007).

cannot be addressed with traditional methods. Conventional safety relay technology has also restricted functionality of safety systems, particularly in terms of flexibility and diagnostics. Kuka Roboter GmbH has developed a safety system for industrial robots incorporating the safety-related fieldbus, SafetyBUS p, in cooperation with Pilz GmbH. The Electronic Safety Circuit (ESC), coupled with SafetyBUS p and Pilz PSS safety controllers, is now being used by BMW at its Body-in-White line in Dingolfing, Germany.
(www.industrialnetworking.co.uk/mag/v9-1/f_safety.html)

Standard automated optical protection devices use laser scanner technology in order to separate the human from the robot. The major supplier for these type of safety systems for automated assembly is the German company SICK (www.sick.de). Fig. 3.15 demonstrates the use of SICK active opto-electronic protection devices (AOPD) in assembly.

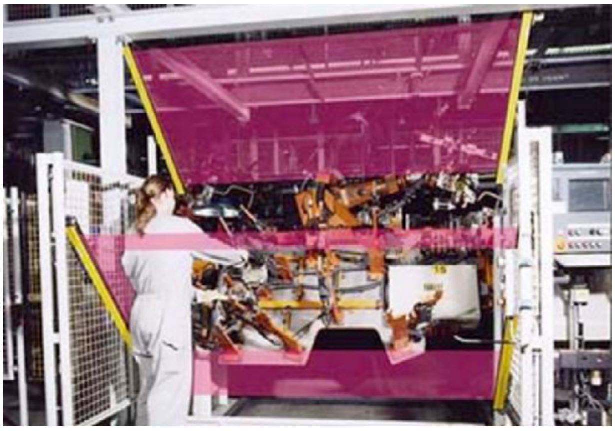


Figura 3.15: Application of active opto-electronic protection devices in assembly.

SafetyEYE by Pilz is a camera System for 3D workplace surveillance (Fig. 3.16). It is meant to erase the need for safety fences separating the robot workspace from the worker (www.pilz.de/products/sensors/camera/f/safetyeye/index.jsp).

The system has a sensing device, a computer, and a programmable safety and control system. The sensing device has three cameras (Fig. 3.16 left part). The computer receives the camera's image data via fiber-optic cables and creates a three-dimensional image using complex algorithms. This image is then superimposed over the detection zones image to see any zone violation. The computer gives results to the safety system controller, which is the interface to the machine controller. If a detection zone has been violated, the configurable outputs are shut down. Typically, the sensing device is located above the workstation for an overview of the robot's operating range (Fig. 3.16 right part). When a worker enters the immediate danger zone, there will be an emergency stop to the work. When a worker enters the zone where the robot would take several seconds to reach, the controls reduce the robot speed. When the worker steps back, the robot returns to normal speed.

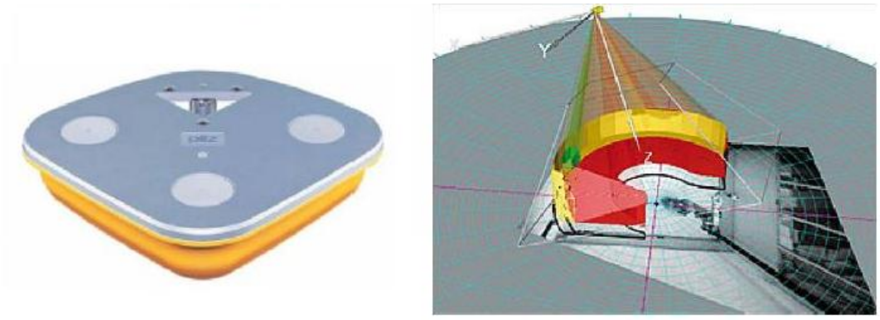
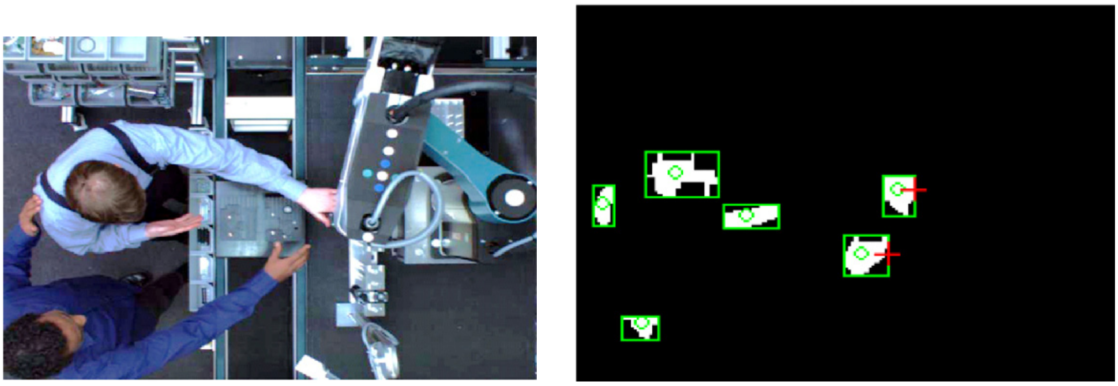


Figura 3.16: SafetyEYE camera for workplace surveillance.

For safe human-robot interaction besides sensor and interaction concepts the robot control architecture is an important component to ensure safe operation of the robot. Therefore failsafe robot controllers are developed which enable the worker to be resident in robots workspace during operation. The first safe robot control was developed by Kuka followed by solutions by Reis, ABB and Fanuc (Kochan A, 2006). Kuka's solution is strictly software based and relies on the severely improved system response time to failures by handing over safety responsibilities directly to the robot controller. The solution by Reis in contrast relies on an additional safety controller monitoring robot operation. This results in a redundant control architecture. The different concepts enable a worker to enter the robot's workspace while the task is still in progress by slowing robot operation to a safe motion speed.

For close forms of cooperation, it is essential not only to detect motion in 3D but also to have an exact surveillance of the worker body. A stereoscopic approach for 3D tracking of the worker body was developed by Fraunhofer IPK in a cooperation with Fraunhofer IPA within the project team@work (Krüger J et al. 2005). The system is able to detect segments of skin within the images

(Fig. 3.17b) in order to find characteristic points of the body. Based on this skin detection the photogrammetric 3D capturing of the body is processed.



(a) *Live image.* (b) *Detected relevant areas.*

Figura 3.17: Stereo camera based surveillance of human-robot-cooperation.

Another system that enables close forms of cooperation is a PMD camera based flexible workspace surveillance system developed by Fraunhofer IPA. The concept of this system is to use the cameras distance data and the robot joint angles as input, and to generate a signal as output which can switch between no risk, warn and stop (Winkler B, 2007).

The acquired distance data from the PMD camera is being preprocessed, the foreground extracted, rectified and meshed in Cartesian space to get the surface of the objects residing inside the workspace. Additionally, the robot is being modelled online in Cartesian space. By comparing both object representations, robot model and objects seen from the camera, the robot can be identified inside the camera object data. All no-robot-data is treated as obstacle and evaluated against safety areas surrounding the robot.

Fig. 3.18 shows how a person whose arm is intruding into the dynamic safety area of the robot can be detected with this system.

Krüger et al. (2007) developed PMD camera based methods for human motion analysis, which can be applied for workspace surveillance as well as for synchronisation of human and robot motion in cooperative assembly tasks.

Post-collision systems

Robot integrated sensors and light weight structures

Joint torque sensing, together with a good robot model are used within the LWR software for fast detection of collision or failure by an integrated torque observer. Inputs to the observer are the joint torques and motor positions. In order to indicate the resulting level of injury, so-called severity indices were evaluated. In the following section the results of the Head Injury Criterion (HIC) are shown, but

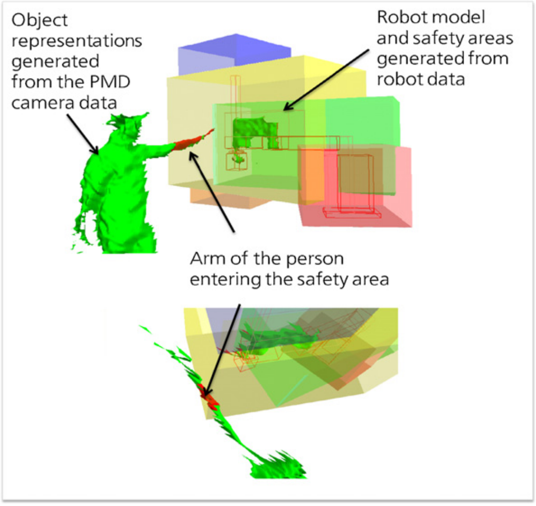


Figura 3.18: Detection of a persons intruding arm: triangles marked in red are located inside the yellow safety area.

other indices for the head, neck, and chest were measured as well. The HIC evaluates the resulting head acceleration during an impact. It is the most prominent and widely used measure to quantify the injury level of human beings caused by car accidents and was introduced to robotics in (Bicchi A et al. 2004, Haddadin S et al. 2004). Oberer and Schraft extended these tests to impacts of head, chest and lower extremities applying industrial robots (Fig. 3.19). The resulting Head Injury Index (HIC), the Viscous Criteria (VC) for the chest and the Pubic Symphysis Peak Force (PSPF) for the pelvis are discussed, showing their potential and limitations for the situation in robotics.

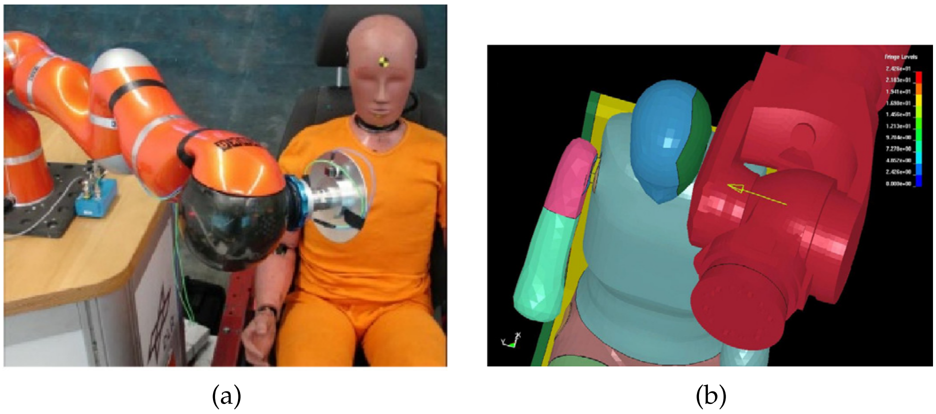

(a) (b)

Figura 3.19: Impact tests performed by DLR and Fraunhofer IPA.

Fig. 3.20 shows the results of HIC-measurements for different types of robots and impact velocities up to 2 m/s. By means of typical severity indices from automobile crash testing even an impact of a huge robot such as the KR500 cannot pose a significant threat to the human head.

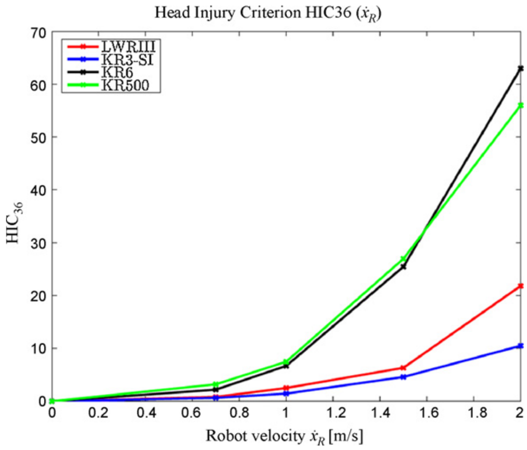


Figura 3.20: Resulting HIC36 values at varying impact velocities for all robots, rated according to the EuroNCAP Assessment Protocol and Biomechanical Limits (Haddadin S et al. 2007).

3.1.4 Component supply and logistics

3.1.4.1 The materials supply challenge

As shown in Section 3.1.3 the developments in robotic assist and handling technology as well as safety systems increase efficiency of cooperative and automated assembly. However the overall time and cost efficiency of assembly processes does not only depend on the optimal relation between human and automation system but also on the question, how assembly parts are fed to cooperative workplaces. As human-machine cooperation targets to higher flexibility and adaptability, the parts feeding process also needs to be highly flexible.

Several unpublished studies performed in Norwegian medium size manufacturing industries have revealed that much of the manual work effort in assembly is not in the primary assembly tasks. The task of fetching components from storage areas and bringing them to the workplace for assembly has in many cases been found to constitute 60-70% of the total work hours spent on assembly.

In automatic assembly solutions it has been found that more than 75% of the equipment cost is on feeders and transport systems that automates the logistics of assembly while the actual assembly operation equipment account for less than 20% of the total cost of a typical assembly line.

Nevertheless, much of the research in assembly automation has been focused on the primary assembly. The automation of logistics and feeding has not been studied to the same level. But this area needs much higher attention if the performance of automatic assembly shall be brought to the same high level as that found in parts manufacturing. Some interesting papers by Bley, Denkena, Jovane et al. has pointed out the challenges and opportunities for greater effectiveness and flexibility in automatic assembly (2003-2006).

The real challenge here is part feeding flexibility. Solutions to automation in feeding and logistics have existed for a long time, dating back to Henry Ford's assembly line for his model T automobile. But the majority of these solutions are rigid, mass production types. Where flexibility is called for, in particular where the need is flexibility for manufacture to order with lot sizes down to one unit, good solutions are missing.

3.1.4.2 Flexible gripping devices

The flexibility challenge starts already at the gripping stage. In a cooperative assembly between human and machine, the worker normally carries out complex handling operations, where the high senso-motoric abilities of the human hand are needed. Robots are inherently very flexible, but their performance is often limited by the ability to grip the object that shall be handled. Grippers that can handle the variety from hard to soft and limp materials are not commonly in use industrially, and the technology in this area is still developing.

In particular the problem of changing quickly between different gripping tasks is a challenge. This problem encompasses both the robot movement program and the gripper design. Much advanced work has been performed on universal multi-finger grippers, but these solutions have not seen any applications in ordinary industrial tasks. Furthermore there is a challenge in size variations, how to enable the same gripping device to switch between handling objects of millimeter size and meter size.

- Humanoid multi-finger grippers.
- Special purpose gripping systems.
- Gripping of limp, soft and "non-definite shape" objects.
- Large size range gripping.

3.1.4.3 Intelligent gripping

Fig. 3.21 shows the spectrum of today's gripping systems.

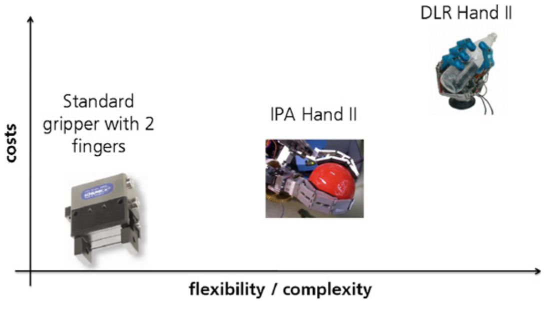


Figura 3.21: Spectrum of today's gripping systems (Wegener K, 2007).

This figure is based on a classification of grippers with two criteria: flexibility and complexity of a gripper and costs of a gripper. This spectrum has two extreme positions: A two finger standard gripper is in the lower left corner of Fig. 3.21. On the one hand a two finger standard gripper has only a very low flexibility, but is on the other a very cost effective gripping system.

Complex hands like the DLR hand II or the Schunk SAH (Schunk Anthropomorphe Hand) (Fig. 3.22) are very complex gripping systems with several degrees of freedom. But the price of these systems can easily exceed the price of a robot system.

- Sensory systems for grippers.
- Picking unordered objects.
- Search mechanisms in gripping.

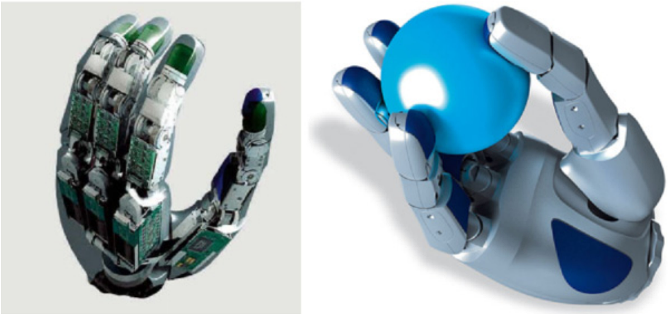


Figura 3.22: Anthropomorph hand (www.de.schunk.com).

In order to fill the gap between these two extreme gripping systems Fraunhofer IPA developed the IPA hand I and the IPA hand II (Fig. 3.23) which is a good compromise between the flexibility and costs.

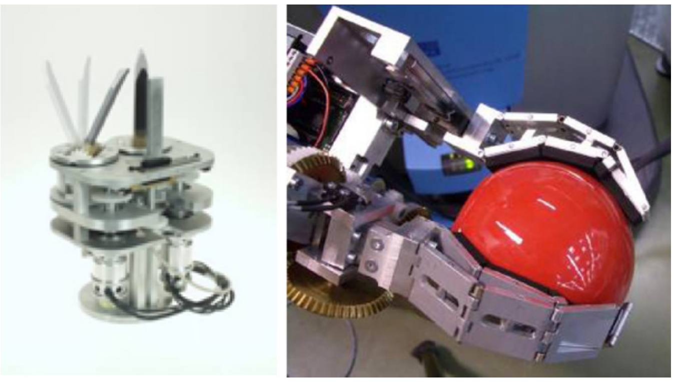


Figura 3.23: IPA hands I and II.

Both hands provide three possible gripping configurations (2 finger parallel, 3 fingers lateral and 3 fingers centric), which enable to grip a large number of different objects. Furthermore, both hands have a limited number of electric drives (the IPA hand I for example just needs 2 drives), and thus they provide a good cost effectiveness.

The IPA hand II is additionally equipped with a bio-inspired finger kinematics. This so-called Finray effect enables a self adaptation of the fingers to the objects that have to be gripped (Wengwner K, 2007).

3.1.4.4 General feeding subtasks

All automation solutions in manufacturing, whether it is in machining or cooperative assembly relies on some sort of automatic part feeding system to operate. Feeding parts into an operation is essential for all manufacturing operations; therefore automated as well as cooperative assembly requires automation of this process. Automatic feeding has however proved to be rather challenging because of the large diversity of parts. Even today there is no general theory or methodology that gives a straight road forward to an automation solution. There are on the other hand large libraries of solutions that can be applied to specific subclasses of the general class of automatic feeding.

To obtain an understanding of the feeding problem it is necessary to subdivide the general task into typical task classes that depend on component characteristics as well as process characteristics. Langmoen (1983) and Rampersad (1994) have proposed classification according to the following criteria:

- Production batch volume of a given unique component:
  - Large (mass production)
  - Medium
  - Small and single piece (produce to order)
- Component size:
  - Large (characteristic dimension >1m)
  - Medium (characteristic size between 100 mm and 1 m)
  - Small (characteristic size between 1 mm and 100 mm)
  - Miniature (characteristic size < 1 mm)
- Component complexity:
  - Simple shape, symmetric or semi symmetric
  - Unsymmetrical but simple shape
  - Complex shape
- Component stiffness:
  - Stiff, non-deformable objects
  - Semi stiff, deformable (like meat, rubber components, wires, etc.)

  - Limp objects (like textile, tissues, thin plastic sheets, etc.)
- Fragility:
  - Unbreakable by normal handling
  - Moderately fragile (requires some attention to handling forces)
  - Very fragile (must be handled very delicately).

This criteria list is not exhaustive, but it expresses the fact that very different considerations have to be taken into account when a cooperative or automated assembly system is considered. In the development of feeding systems such criteria can be used systematically to evaluate possible solutions and the likelihood of obtaining an efficient, workable automatic feeding solution.

3.1.4.5 Design for assembly applied to feeding problems

Formalized methods of analysis with respect to feeding systems exist. Boothroyd (2005) developed an analysis method as early as 1979. This method focuses mainly on geometrical properties of the part and assumes high volume production. Later an alternative analysis method was proposed by Lien et al. (1982). In this analysis more parameters are used so that stiffness, fragility and size are brought into consideration. These two methods have both their shortcomings. This was realized by Rampersad (1994) who has tried to combine the best elements from Boothroyd and Lien into the "House of Assembly" method. The house of assembly also introduces some QFD elements in the analysis. Furthermore there is a Japanese method for assembly automation analysis, the AREM (Suzuki T et al. 2001). This method relies on an expert evaluation of the automation solution. Common to all of these methods is the idea that the complexity of feeding and assembly can be characterized by some figure that expresses complexity of the feeding task. In the Boothroyd analysis method which has been trademarked DFMA there is in addition a calculation formula allowing the estimate of the cost of feeding and assembling a component (Boothroyd G, 2005). This formula is limited to certain cases of automatic assembly in the large volume segment.

3.1.4.6 Sub-problems of the feeding task

The feeding task can be subdivided into four major steps; each of them requiring unique and very different techniques for automation. This subdivision assumes that the components initially are stored in large numbers in bulk, not oriented and fairly close, in the order of one meter or less, from the point of usage. Given this border condition, the feeding task comprises the following steps according to several authors (Rampersad HK 1994, Boothroyd G 2005, Estesen L et al. 1980-1982, Pherson D et al. 1984):

- *Separation*: One unique component is separated from the bulk volume.
- *Transfer*: The component is brought to a point very close to the point of pick up or treatment in the next stage of the manufacturing operation.
- *Orientation*: The component is brought from a general orientation into the specifically wanted orientation for the operation next in the process.
- *Positioning*: The component is positioned precisely within required tolerances for the next handling step in the process.

Some feeder techniques combine all these steps into one feeding device or system. Such systems are the most common ones in large volume manufacturing where small rigid parts are handled. For large parts, small volume, limp or fragile parts it is more common to see these steps of feeding separated.

3.1.4.7 Feeders for small parts in large volume production

Boothroyd (2005) has described 17 basic feeder principles and mechanisms that are suitable for large volume manufacturing. It is characteristic that all of these combine mechanisms for the four subtasks of feeding into one device. It is common though that separation and transportation is related one part of the mechanism while orientation and positioning is relying on additional elements of the system. In addition, the orientation techniques are in some respects generic so that they may be applied in different feeding systems. Among the feeders described by Boothroyd only a few have been widely put to use. These are:

- vibratory bowl feeder,
- elevator feeder,
- belt feeder and
- drum feeder.

Some of these feeder techniques are very old as a basic principle. The vibratory bowl feeder is one of them. Still it has the reputation for being the most used feeder principle because of its simplicity and reliability. Over the last year some more flexible and sophisticated feeders have emerged.

The basic belt feeder as described by Pherson et al. (1984) has been used as basis for several developments that increase its flexibility and reconfigurability. Pherson describes a system that uses simple photocell sensors to detect various part orientations. Active elements like pneumatically operated wiper blades are used to wipe away incorrectly oriented parts. The belt feeder is also the backbone of systems that use camera based active orientation.

The need for gentle feeding for particularly sensitive parts has led to the development of the vibratory brush feeder (Fig. 3.24). This feeder has the advantage of silent operation and small risk of surface damage of the part due to the part falling into a bulk storage area.

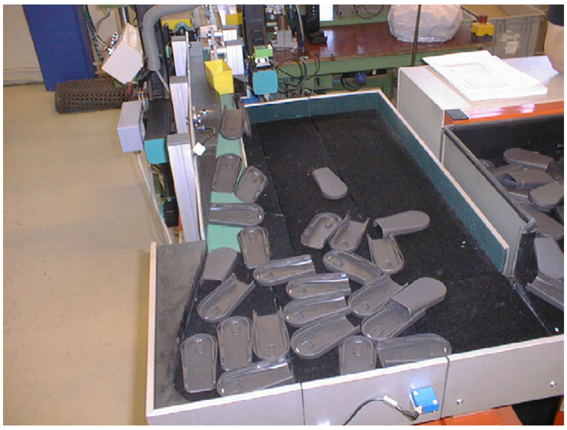


Figura 3.24: Vibratory brush feeder for gentle feeding of fragile parts.

Moving step elevators represent another variation of recently developed feeders. This elevator is also more gentle in its handling as compared to ordinary elevator feeders. But it has not had great impact in the feeder market probably due to its somewhat complicated feeding mechanism.

In spite of many options for feeding, the vibratory bowl feeder (Fig. 3.25) is the leading device by a solid margin. Its simplicity, versatility and reliability are the major reasons for its popularity. Despite this, it is one of the most typical "one part only feeders" which means that it can only be used efficiently for the specific part for which it is designed. This is mainly due to the fact that orientation devices are strongly integrated in the feeder design.

Figura 3.25: Vibratory bowl feeder with active sensing reorientation. The vision system identifies the component for pick up. Unsuitably positioned components are returned to the bowl by a pneumatic pusher.

3.1.4.8 Large part feeding

The feeding of large parts seems to be a much more complex task than feeding of smaller parts. While small part feeders can accept parts in disordered bulk fashion large part feeding systems cannot operate the same way.

The borderline between small part and large part feeding is not very clear. But some indications about the borderline can be found in the rule of thumb saying that a vibratory bowl feeder should have a bowl diameter of approximately 10 times the largest dimension of the part to feed. For practical reasons bowl feeders are limited in size to around 1 m bowl diameter, setting the borderline between small and large parts to 100 mm.

In other studies (Estensen L, 1980) the borderline has been set to 150-200 mm. But there is no clear indication that this is a well defined borderline. It seems more to be a type of border set by the upper size limit for available feeders for bulk components.

Truly large parts can be seen as components having at least one dimension greater than 500 mm. For such parts no universal feeding principles seem to exist. There are however numerous special purpose feeding mechanisms, usually designed for a limited range of shapes and dimensions. Some examples of feeders in this category are:

- sheet metal feeders for stacked sheet metal,
- tube feeders and bar feeders for raw material to sawing and machining operations and
- de-stackers for cardboard in box raising equipment.

These feeders are only usable for materials with smooth surfaces like straight, un-machined bars and tubes, flat plate material and cardboard and other large component with clean simple shapes (Li HF et al. 2002, Liao X et al. 2003). As soon as the part becomes formed into something “un-straight” none of these feeding principles are usable in their basic form. The feeding of more complex shapes thus has no general solutions available, nor does the literature give any indication of theoretical solutions for these large part feeding challenges.

3.1.4.9 Orientation mechanisms

Orientation of the component is an essential part of a feeder system. Bringing the part into its required orientation is a necessity for the next step in almost all manufacturing or assembly operations. Orientation devices are often seen as integrated parts of the feeder. But in almost all cases the orientation can be seen as a function independent from the separation and transportation part of feeding.

Basically there are two principles used for orientation (Boothroyd G, 2005):

- Passive orientation which utilizes the potential and movement energy to create the necessary force to reorient or eject an incorrectly oriented part.
- Active orientation uses externally supplied energy to either reorient or eject incorrectly oriented parts.

In addition two different sensing methods are used to sense the part's orientation:

- Intrinsic sensing, that is utilization of geometrical features of the part to create the reorientation or sorting action. This is normally associated with passive orientation but can also to some extent be combined with active orientation. It is the only method available for sensing with passive orientation since it requires no external energy supply.
- External sensing utilizing some sort of sensing devices that can observe features that indicates the orientation of the part and can supply information from this observation to an active orientation device. Most active orientation devices rely on external sensing.

Passive orientation

Designing passive orientation relies to a large degree on the experience of the designer. But Boothroyd (2005) has presented a library of passive orientation elements. The library is atomic in the way that each element shall have only one orientation effect (like reorientation around one axis). The wanted reorientation device for a specific part is then composed by selecting the orientation device elements that can give the wanted effect based on the available external geometrical features of the part. Edwardsen (1995) has taken this as step further by investigating the properties of some reorientation devices and combining that with the movement pattern and energy available from a vibratory feeder to create a basis for precise prediction of the reorientation effect.

Nevertheless, all passive orientation methods are based on fixed geometrical elements that are not easily reconfigured. So even if reconfiguration is possible, the method usually requires manual effort with the associated time for reconfiguration. Therefore the passive orientation is still a method mainly suitable for mass production automation.

Active assisted gravity reorientation

In certain cases a hybrid solutions combining active and passive techniques are applied. The typical case is the use of gravity for reorientation, but some sort of active mechanism is applied to make gravity work in the way wanted. The simplest procedure is to push the part into a position where gravity will ensure proper orientation when the part tips over an edge (Estensen L, 1980). Here the part must be fed in a well defined manner so that only the outcomes that give correct orientation after the act of gravity reorientation can occur.

Another more sophisticated method uses vision system in combination with a robot having only 4 DOF that can pick up randomly oriented parts on a table or conveyor. These parts should typically have a length/width ratio greater than one to make the action easier. The robot's two gripper fingers are equippedwith small low-friction pivoting pads as grip area. When a part is lifted off its resting surface by a grip outside its center of gravity it will turn so that its center of gravity comes straight below the centerline between the gripping pads. A 90^0 reorientation around the X or Y axis is thus possible for a robot system with only rotation around the z-axis as a controlled orientation possibility.

These two examples show that hybrid reorientation systems that combine gravity with some sort of active repositioning can work efficiently in certain applications.

Active sensing for reorientation

- *Single point external sensing*: Point or single feature sensing, like micro-switches, photocells, inductive or fluidic sensors identify one single feature of the part. These devices are simple and reliable and can usually be applied to the actuation of one simple reorientation action. There are numerous examples of how these sensors are used to obtain a specific reorientation action. But the application of such sensing devices does seldom lead to greater flexibility of the feeder. So basically these sensors are applied in cases where intrinsic sensing is unreliable or cannot be applied.
- *Full feature sensing*: The full feature sensing relies on some kind of mapping of the complete external shape of the part. The most well known method in this area is the electronic camera which gives a two-dimensional image of the part, usually named vision systems. Pugh described the basis of this method in 1983. Since then much of the development in the field has been concentrated on refinement of the methods and development of more cost effective solutions. The general strong reduction in cost for electronic devices has been a major driving force for the strong increase in vision system applications for part orientation.

Some of the solution described in the literature covers sorting out all unwanted orientations and returning them to a new feeding loop. This is a technique applied to vibratory bowl, vibrating brush and belt feeders (Boothroyd G 2005). A more efficient method is use the image information to realign the part when that is possible. This will in general give a substantial increase of the part feeding rate (Fig. 3.26).

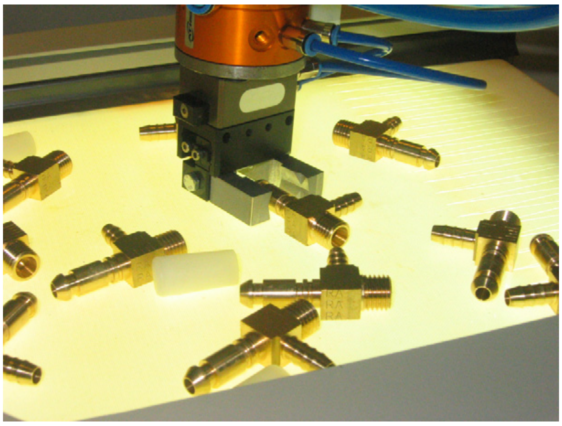


Figura 3.26: Camera equipped belt feeder for feeding and picking arbitrarily oriented components.

Two-dimensional imaging has some shortcomings in identifying the orientation of complex three-dimensional shapes. Several methods have been investigated to overcome this.

- *Light section mapping*. In this method thin stripes of light are projected on the part at oblique angles. The light stripes form a pattern that are similar to the sections one would get by cutting the part along the plane of the light projection. Information about the angle of the light-plane combined with the position of points on the two-dimensional image of the light section enables a computation of the three-dimensional points on the parts surface that are seen in the light section. By interpolation between points on different light sections a complete the dimensional image of the part can be generated (Pugh A, 1983).
- *Multi camera three-dimensional vision*. This technique requires at least two cameras. By identification of the same point on the part's surface in two or more images with known position in space the points 3D coordinates relative to the cameras can be computed. The basic principle was described by Pugh. Later there are numerous authors who have described refinements of this method (Harris L et al. 1993). Today the method works particularly well in cases where sharp corners and edges are visible so that edge detecting methods can be utilized to identify "same point" in two images.

The vision technology is slowly put to use in industry. Some interesting applications have been reported like sorting of castings in automotive part manufacturing (Baumann R 1982, Jermann JP 1983) and robot based automation of flow assembly lines (Redford AH, 1986). But these applications also reveal some practical challenges in keeping the camera systems operative in the sometimes rather harsh industrial environments.

3.1.4.10 Flexible component feeders

The state of the art in feeding is basically centered on the concept having a specialized feeder for each part. In recent research projects there has been a concentration on finding more flexible feeding principles that will handle variants of parts without mechanical rebuilding. In recent years such systems have appeared in industrial applications. These systems work well with certain applications (Boothroyd G 2005, Redford AH 1986, Suzuki et al. 1980).

The basic principle of multiple part feeding is to use the simple belt feeder introduced by Pherson (1984) as a simple separator mechanism that presents the component on a surface where it can be easily detected. Then a suitable detection mechanism can be applied to identify individual parts and determine its location and orientation.

The grip action shown in Fig. 3.27 is a typical example of a gripping of one type of part among others.

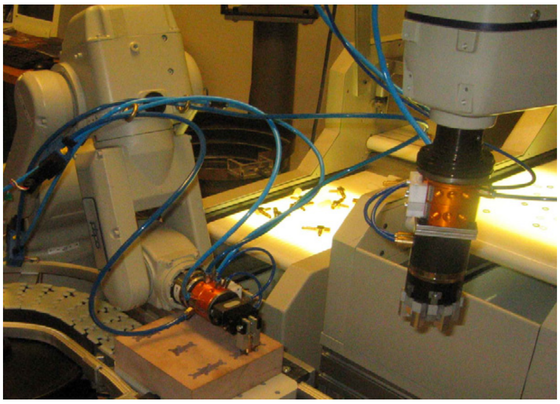


Figura 3.27: Adept Flexfeeders for multi component feeding using electronic vision for component identification.

Laboratory experiments in the NTNU assembly laboratory as shown in Fig. 3.28 have shown though that the time required to identify one single component among several different ones can take considerable time.

The time for the automatic picking procedure will be longer than what can be obtained with dedicated feeder and orientation systems. But the advantage is that a changeover between parts can be performed very quickly, there is hardly any need for hardware changes. And for previously used components the software templates will be available and immediately applicable. The main challenge in flexible feeding seems to be the time required to empty a feeder of one type and replenish it with another type of component.

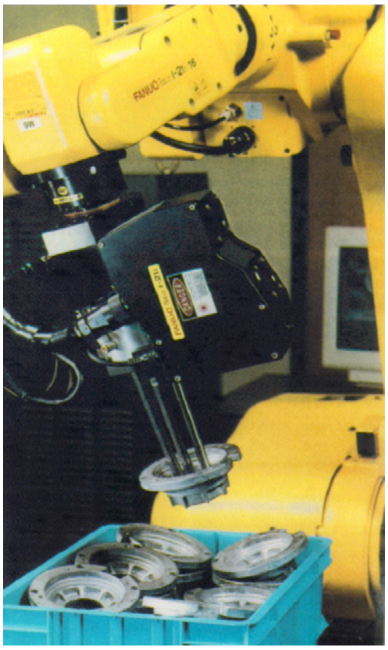


Figura 3.28: Camera and force controlled gripper fingers used to pick up unordered castings [Fanuc].

Another way of looking at flexible feeding is to eliminate the special feeding device altogether and rely on sensory system equipped robots for the heavy and monotonous task of picking components either from conveyors or out of storage bins. Here developments of bin picking systems show promises.

Fanuc has introduced a system that combines an arm mounted camera system with force sensors in the grippers that enables the robot to pick parts directly from a container or from a conveyor.

3.1.4.11 Flexible automated logistics

Advanced automated guided vehicle systems

The feeding of component feeders is another challenge. Automatic operation of assembly systems requires a steady flow of components from intermediate storage or part manufacture directly before assembly. Traditionally this section of the manufacturing system has been automated to a lesser degree since the frequency of operations is lower, and consequently the apparent economic justification is harder to reach.

But also in this area there are technical developments that points towards more flexible automatic transport solutions. Automated guided vehicle (AGV) technology has been used for many years, particularly in warehousing and large scale manufacturing (Bostelman RV et al. 2005, Correa et al. 2007, Lin L et al. 2006, Maughan FG et al. 2000). This technology is now ready for a new step forward with the emergence of low cost advanced electronic systems and autonomous navigation systems that will make modern AGVs more cost effective and flexible, and thus also applicable to a much wider range of assembly systems (Yamada Y et al. 2003, Yoo J-W et al. 2005, Zhang Z et al. 2005).

In particular the emergence of trackless AGV systems bears promises of more efficient and flexible autonomous transport devices. In trackless solutions no fixed guide wires are needed. Instead of this the transport vehicle uses either onboard navigation systems that rely on observing fixed landmarks for navigation, or they use information transmitted from cameras in the area they move to get overall information about their position. These systems require much less of costly fixed guidance systems and are thus much easier to deploy and reconfigure.

Intelligent conveyor systems

Intelligent conveyor systems are other important new developments. Conveyors have gone from being simple belt systems with a constant conveying speed to becoming complex transportation systems that can route individual objects along paths that are tailored to the needs of a specific manufacturing process. The routes available will always be limited to those offered by the tracks laid down, but within these there are opportunities for much greater flexibility than in the old rigid one-way systems.

Systems frequently use some sort of identification system on transport bases (pallets) to determine the routing of each individual transport unit. It is thus possible to mix different products in different stages of the production process on one transport system. Each individual transport unit will be routed to its destination at each conveyor intersection according to the production process for this part as represented in the overall control system of the conveyor.

This type of transport enables the combination of manual and automatic stations along a core transport line. It also enables the combination of serial and parallel work stations in a process to obtain the most efficient utilization of the manual work force and the automatic machines in hybrid assembly lines as shown by Lien (2001). The use of manual workers for the complex finishing tasks on assembly lines give both greater capacity flexibility and higher overall productivity than fixed sequential assembly systems without the possibility for intelligent rerouting.

3.1.4.12 Intelligent warehousing

One challenge in assembly is to keep track of the amount in stock at all storage points in a system. This challenge becomes very large when the process is automated. Out of stock situations at any point lead to immediate stop of operations, and the need for manual intervention to replenish and restart.

Today we see very little of true automatic storekeeping applied to automated assembly systems. But the need is there. An assembly flow control system that keeps track of all the components in the system and orders replenishment to all storage points is needed for a system to operate truly automatic.

Today's ERP systems are well developed to handle the overall bookkeeping of the main storage areas in a company, i.e. raw materials, intermediate stock and finished goods. But the stock level of any of these storage areas is not updated in real time. For tight down to the minute follow up of production the ERP system is thus unable to provide exact information. In addition all the work in progress stock outside of the main storage areas is normally not kept track off. Thus there is a large "white spot" on the storage map in most factories. The problem of this "white spot" is overcome by most foremen and department managers through local notebook storekeeping to cover the needs of any department.

The developments in new sensor technology, in particular the development of RFID, offers great potentials for building solutions that have real time information about the status of all storage points (Djassemi M et al. 2005, Ramamurthy H et al. 2005, Ranky PG 2006). These solutions should have accuracy of one unit which is necessary for reliable automatic operation. Such planning and monitoring systems are not yet available on the market. But the demand from industry for a tighter, real time control of all work in progress stock levels is increasing. At NTNU two ongoing research program address this task in an effort to develop next generation Manufacturing Execution Systems (MES) with real time stock control. The emergence of such systems will enable a more precise supply of components for assembly and minimize time loss due to out of stock situations.

3.1.4.13 Parts feeding with intelligent assist devices

An efficient cooperation of human and machine in assembly can often be realized in a way where the feeding of the assembly parts is executed by an automated handling system but the assembly process itself is carried out by the human worker. When a close interaction with contact of human and feeding system is possible with respect to safety requirements, the robotic feeding system may not only feed the assembly workpiece but also support the worker with positioning functionality.

Fig. 3.29 shows a cobotic rail crane system design from Fraunhofer IPK, which provides feeding of large assembly parts as well as support for positioning. For the safe and efficient interaction, the intelligent automation device also provides functionality for collision avoidance. Additionally, in order to give the worker free space for his work, the cobotic system after feeding returns to a defined position executing the so-called homing function.

Figura 3.29: Cobotic system for feeding and positioning of large assembly parts.

3.1.5 Organizational and economic aspects

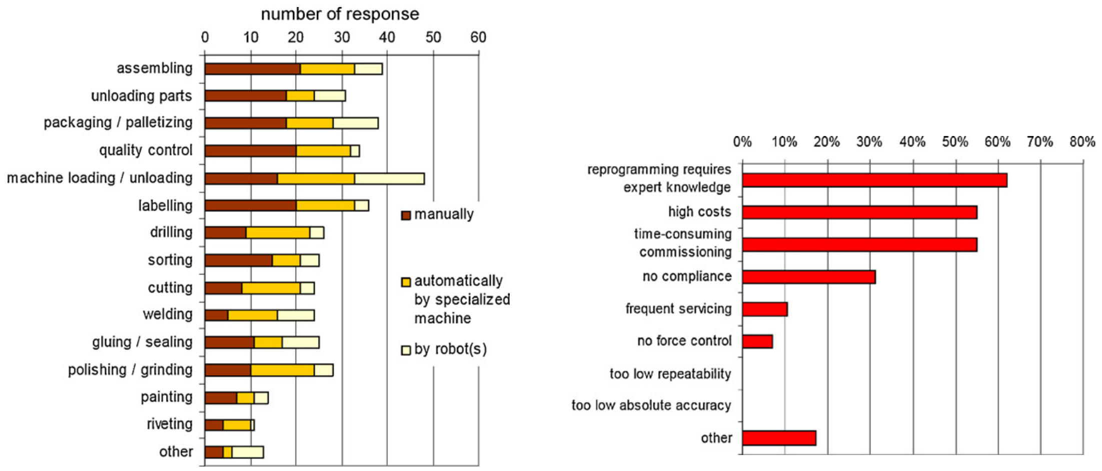
3.1.5.1 Requirements for flexible robot based automation

The ARFLEX project funded within the 6th Framework programme of the EU aims to enhance and extend the capabilities of a common industrial robot system. By means of advance control system and intelligent sensor devices ARFLEX displaces nonreconfigurable, proprietary and expensive automation technologies. Kus et al. (2008) analysed the requirements of small and medium enterprises (SME). The investigation was carried out among enterprises in Germany, Italy, Poland and Switzerland. The analysis contained questions related to the robotisation of the production line, the activities performed manually, automatically by the use of specialized machines, and by robots. Figs. 3.30a-3.30d comprise essential results of the investigation, with respect to complexity of robotic systems, production batch sizes and changes in production lines of SME.

The goal of the enquiry concerned the identification of the limitations and imperfections of the robotic systems having the biggest influence on their deployment in the industrial applications.

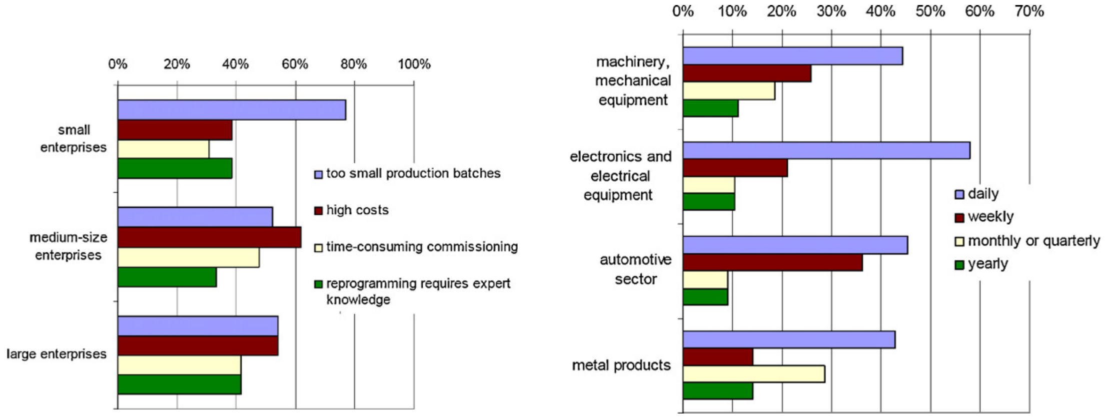
In case of small enterprises the main hindrance is too small production batches. This result indicates that the market is still not served with solutions satisfying the requirements of the low volume production system. In case of the medium-size enterprises, the deployment of the industrial robots is mainly limited by the high costs.

The most frequent batch changes can be observed in electronics and electrical equipment production. In this sector almost 60% of the batch changes consider the daily changes in the production. Also in other industrial sectors the daily changes in the production line are also prevailing and are more than 40%.



(a) *Activities performed manually, automatically by specialized machines and by robots in the enterprises where robots are installed.*

(b) *Main disadvantages of using the robot in industrial applications.*



(c) *The main obstacles for the dissemination of the robotic technology with respect to the size of the enterprise.*

(d) *The frequency of the changes in the production line (batch change) with respect to the industrial sector.*

Figura 3.30: Essential results of the investigation.

3.1.5.2 Hybrid automation cost assessment

Fig. 3.31 shows the assumed cost potentials of hybrid automation compared with robotic workcells and automated transfer lines. According to this, hybrid automation has the biggest economic benefit in small and medium sized productions.

A more specific way to asses the costs of hybrid automation is the net present value (NPV), which is the sum of all cash inflow and outflow discounted back to its present value.

The following example shows how this method can be applied to assess the costs of hybrid automation. This example bases on the PowerMate example (Schrft RD et al. 2005) shown in Section 3.1.2.3. Thus, the assembly consists

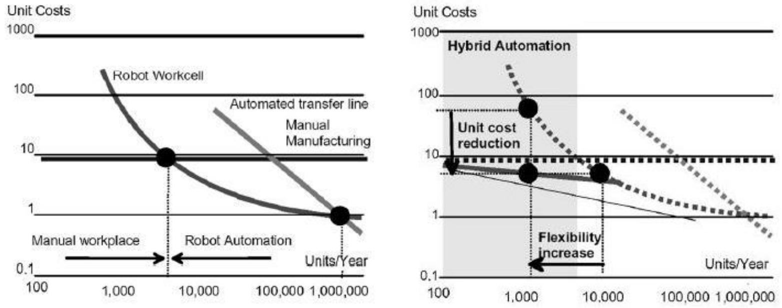


Figura 3.31: Reduction of robot system costs compared to labour cost (left) and assumed cost potentials of future hybrid automation (right).

of the following tasks:

Task 1: Prepare part A.
Task 2: Grip part B out of bin.
Task 3: Move B to A.
Task 4: Precise positioning B.
Task 5: Assembly A and B to AB.
Task 6: Move part AB to part C.

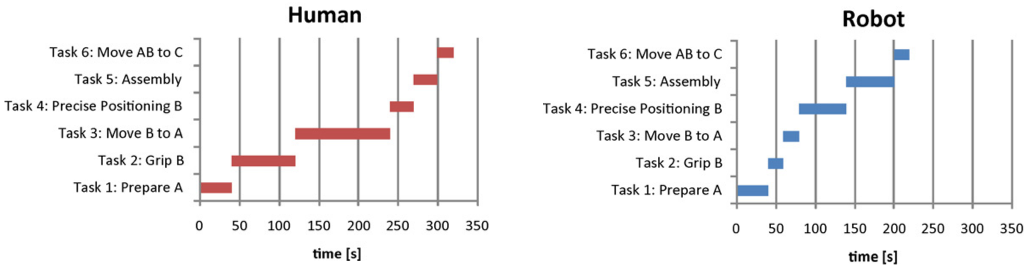
As mentioned earlier tasks like handling of huge and heavy objects can be more efficient with robots while assembly tasks where high sensory skills are required can be more efficient with human beings. As consequence the tact times for a task differ if they are done by a robot, by a human being or in a hybrid automation scenario. Table 3.1 compares tact times of human and robot for the task sequence example.

Tabella 3.1: Tact time comparison between human and robot.

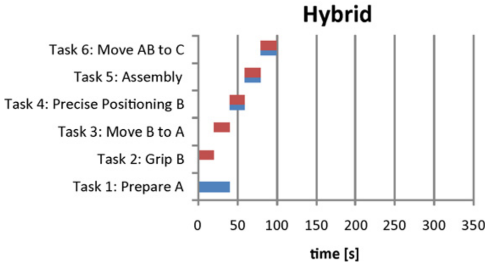
Tact times in [s]	Robot: all tasks sequentially	Human: all tasks sequentially	1 and 2,3 parallel, rest sequentially	Best of
Task 1: Prepare A	40	40	40	40
Task 2: Grip B	20	80	20	20
Task 3: Move B to A	20	120	20	20
Task 4: Precise positioning B	60	30	20	30
Task 5: Assembly	60	30	20	30
Task 6: Move AB to C	20	20	20	20
Total tact time	220	320	100	160

Furthermore, in a hybrid automation scenario human worker and robot can work in parallel. In this scenario the task 1 can be done by the human worker while the robot performs tasks 2 and 3. As consequence the tact time of the hybrid system reduces to 100 s (instead of 140 s).

The tact time diagrams (Figs. 3.32a-3.32c) for these three alternatives look as follows.



(a) *human solution.* (b) *robotic solution.*



(c) *hybrid solution.*

Figura 3.32: Tact time diagram.

Assuming that the needed output is 75,000 parts AB per year and that this company is producing in 2 shifts á 8 h at 200 days per year, the company will need either (Table 3.2):

- 10 (9.6) workers (human solution) or
- 3 (2.2) robot systems (automated solution) or
- 1 hybrid system with 3 human workers and 1 robot.

Furthermore we assume the following cash inflows and outflows for the investments.

According to these cash flows as the estimated numbers of human workers, workplaces and robot cells the three alternative solutions will reach the following net present values (Table 3.3):

- *manual solution*: $760,238.93$ €
- *robotic solution*: $2,117,849.19$ €
- *hybrid solution*: $2,754,257.19$ €

Table 3.4 shows as an example the calculation of the net present value (NPV) of the hybrid solution, which is according to the NPV method the best solution.

Tabella 3.2: Output calculation for human, robot and hybrid system assembly.

	Robot	Human	Hybrid 1
Total tact time [s/pc]	220.0	320.0	100.0
Output per hour [pcs/h]	16.4	11.3	36.0
Hours per shift [h/shift]	8.0	8.0	8.0
Shifts per day [shifts/d]	3.0	3.0	3.0
Work days per year [d/a]	250.0	250.0	250.0
Total work time per year [h/a]	6,000.0	6,000.0	6,000.0
Output per year of 1 system [pcs/a]	98,181.8	67,500.0	216,000.0
Requested output per year [pcs/a]	215,000.0	215,000.0	215,000.0
Needed robots (integer)	3.0	0.0	1.0
Needed humans per shift	0.0	4.0	1.0
Needed humans total	0.0	12.0	3.0

Tabella 3.3: Cost comparison between human, robot and hybrid system assembly.

	Robot	Human	Hybrid 1
Invest per robot eel	0.00 €	−300, 000.00 €	−325, 000.00 €
Invest per workplace	−10, 000.00 €	0.00 €	−15, 000.00 €
Variable costs for robot cell p.a.	0.00 €	−5, 000.00 €	−5, 000.00 €
Variable costs for human worker p.a.	−50, 000.00 €	0.00 €	−55, 000.00 €
Revenues p.a.	750, 000.00 €	750, 000.00 €	750, 000.00 €
Interest rate	10%	10%	10%

Tabella 3.4: NPV calculation for hybrid system assembly.

Hybrid	Outflow	Inflow	DCF
Year 0	−340, 000.00 €	0.00 €	−340, 000.00 €
Year 1	−170, 000.00 €	750, 000.00 €	527, 272.73 €
Year 2	−170, 000.00 €	750, 000.00 €	479, 338.84 €
Year 3	−170, 000.00 €	750, 000.00 €	435, 762.58 €
Year 4	−170, 000.00 €	750, 000.00 €	396, 147.80 €
Year 5	−170, 000.00 €	750, 000.00 €	360, 134.37 €
Year 6	−170, 000.00 €	750, 000.00 €	327, 394.88 €
Year 7	−170, 000.00 €	750, 000.00 €	297, 631.71 €
Year 8	−170, 000.00 €	750, 000.00 €	270, 574.28 €
NPV			2, 754, 257.19 €

This calculation is based on several assumptions, e.g. that all alternatives produce the same quality and that all tasks can be done by a robot and by a human being. Furthermore aspects of illness of human workers and holiday regulations have not been not taken into account. Nevertheless, this example shows that a high reduction of the tact time of a hybrid system compared to the manual solution and to the automated solution can be a good basis for economic advantages of hybrid solutions.

Lotter and Wiendahl (2006) examined the performance of hybrid assembly systems, which include automated feeding and provisioning of parts. By this process time, which is not directly used for the assembly task can be reduced significantly and the overall efficiency of the production process is increased. This type of hybrid assembly was regarded in comparison with fully automated assembly for different products. In six of seven examined cases the costs per piece of a hybrid assembly were smaller than those of a fully automated assembly. The cost analysis given in Lotter and Wiendahl (2006) shows for the electric motors that the costs for a hybrid assembly cells needed for an output of 3000 pieces per day and also two cells needed for up to 6000 pieces per day are lower than those of a fully automated assembly system.

Beside other advantages of hybrid systems are:

- hybrid systems represent a form of rationalisation with an integration of human and by this giving positive impulses for occupation,
- assembly costs per piece for hybrid assembly are competitive for a wide range of lot sizes compared with fully automated systems,
- assembly costs per piece for hybrid assembly systems are economic even for relatively low lot sizes,
- the use of hybrid systems is characterized by relatively low investment, which helps to avoid false investments,
- the low degree of automation of hybrid systems increases their reuse value for a new product after finishing the production of an old one (Lotter and Wiendahl, 2006).

Further sources of economic advantages of hybrid solutions might be that a hybrid solution will produce a better quality or that some tasks in a given assembly scenario cannot or can only with high efforts be done with a manual solution or with an automated solution.

Based on experience achieved with intelligent automation devices (IADs) in assembly tasks, Stanley Automation estimates a reduction of injury costs, management costs and labour costs, which in total may reach an amount of 58% thus leading to a payback time of less than 1 month.
(www.stanleyassembly.com/documents/en/VisteonCaseStudy.pdf.) (Fig. 3.33).

Fig. 3.34 shows an intelligent assist device which is used for handling of heavy loads. It is the first admittance display prototype in industry. Due to the admittance display structure of the control system the apparent inertia of the load can be reduced by a factor of 10 and more, so that the handling can be performed with low strain of the worker.

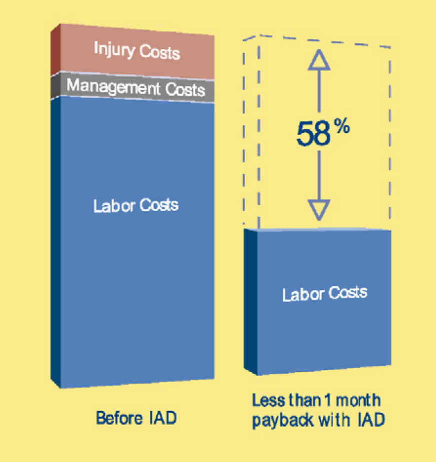


Figura 3.33: Cost reduction by use of intelligent assist devices (IAD).

Figura 3.34: First admittance display prototype in industry (Krüger J et al. 2006).

3.1.5.3 Markets for hybrid assembly systems

In 2007 the worldwide stock of industrial robots reached the amount of about 1 million systems. The yearly supply climbed to about 60,000 industrial robots in Asia/Australia, 30,000 in Europe and about 20,000 systems in the Americas. While handling operations still is the main field of application, other fields differ in these regions. Although automotive industry is still the main customer for industrial robots, a significant growth can be observed in non-automotive sectors such as glass or food industry. Beside others improvements in force sensing, environment recognition, human-machine-interfaces and safety system technology are forecasted to be future technical trends (World Robotics 2008). These trends are significant enablers for hybrid human-robot operation.

An exemplary look to Europe shows the major market conditions for hybrid assembly. For these systems the target industries (automotive, household appliances and aircraft) face strong global competition and represent a major part of the European manufacturing industry. Any effort to improve the competitiveness, productivity and market responsiveness of these industries would be extremely important for Europe. The automotive industry employs 2.2 million people in production in nearly all member states of the EU. There are 380,000 SME's in the supply chain for the automotive industry in Europe. In 2002 global production of passenger cars and light and heavy trucks was just over 59 million units. The main vehicle-producing areas are the Asia-Pacific (19.3 million), western Europe (17.4 million) and North America (16.8 million). The turnover of European carmakers over the last few years has been on average 340 billion Euros per year. The European industry of household appliances employs 200,000 people directly and represents a yearly turnover of about 35 billion Euros. 40,000 SME's are suppliers for that industry. Approximately 50 million large appliances (washing machines, refrigerators, etc.) and 200 million small ones are produced in Europe per year. The aerospace manufacturing industry had in Europe a turnover of 81 billion Euros in 2003. Over 435,000 people are directly employed in high-quality jobs. Its business has a pervasive influence up and down the supply chain, beyond the sector to some 80,000 SME's within the European Union.

3.1.5.4 Hybrid assembly in automotive industry

In automotive industry the degree of automation in assembly mainly depends on two aspects: costs and complexity.

Power train assembly in western European countries is fully automated. Manual operation is typical for assembly of flexible interior parts of the car. In this area, automated handling with a robot is difficult due a lack of automated gripping flexibility and sensitivity and also because of danger of surface damages of the component. Manual or hybrid assembly tasks in automotive production are normally handled within 20-30 assembly stations. According to an unpublished internal analysis of assembly tasks of a major German automotive company, serious savings can be made by use of semi-automated flexible robotic systems for faster feeding of workpieces to the worker. By this, manual work load could be reduced by about 30 min per car.

This can be achieved by a hybrid assembly structure where handling for the final assembly step is fulfilled by use of the outstanding senso-motoric ability of the worker in combination by efficient support by intelligent assist systems (IAS) (World Robotics 2008, Bernhardt R et al. 2007). An important advantage of IAS is the abdication of safety equipment, which normally is needed, when feeding and handling of workpieces is done by robots close to the worker.

In Europe robot based handling and assembly operations determine more than 65% of the robotic market. These are application fields, where higher flexibility of hybrid systems can essentially improve the production process. In Asia and the Americas, cleanroom applications for robotics were increasing whereas assembly was decreasing in 2007 (World Robotics 2008). These facts may be regarded as indicators for a future stronger diffusion of hybrid robot based assembly in Europe compared to Asia and the Americas. The ongoing rapid changes in global markets especially in the automotive sector will have a significant influence to the robot market in the future. The relation between fixed and variable production costs which essentially determines the use of purely automated or hybrid assembly systems will certainly be affected by these dynamic changes.

3.1.6 Conclusion and outlook

The close cooperation of human and machine in hybrid assembly is motivated by the increased need for flexibility, adaptability and reusability of assembly systems. Hybrid assembly systems can essentially reduce the amount of fixed production costs in relation to variable costs. The effectiveness of these systems depends on the lot size, but also on the design of the cooperative workplace and its automated systems. The overall effectiveness of hybrid assembly also depends on the intelligent feeding of workpieces to the cooperative workplace.

An essential precondition for the time efficient close cooperation between human and machine is the safety of the worker. A lot of research has been carried out in this field in recent years and first sensor systems for the surveillance of the interaction between human and robots are available on the market.

The research in the field of intelligent assist devices (IAD) that efficiently support the worker is the basis to keep the worker in the loop in order to utilize his cognitive and senso-motoric advantages for highly flexible assembly. The support functions of IADs comprise safety as well as reduction of physical strain and efficient synchronisation between worker and automated systems.

Future research will have to focus on different aspects for highly cooperative hybrid assembly. The robustness of the system parts for safety, load reduction and others will have to be increased in order to extend the field of applications. A new challenge will be to improve the cooperation of human and machine not only for a single human but also for a group of workers that have to fulfil a common task supported by one or more machines at the same time (Fig. 3.35).

The close cooperation between human and machine may in the future also change the way that automated systems will be programmed. It can be foreseen, that a wide range of automated cinematic systems such as robots will in the future include interfaces for efficient teach modes based on the direct force coupled interaction between human and robot.

The human oriented automation approach may generally lead to a change in the design principles for robots. Today design of industrial robots is focused for accuracy. Control with application of external sensors is needed for stable and safe interaction. In long term solutions the design of intrinsically safe robots will focus on safety and sophisticated control will provide accuracy.

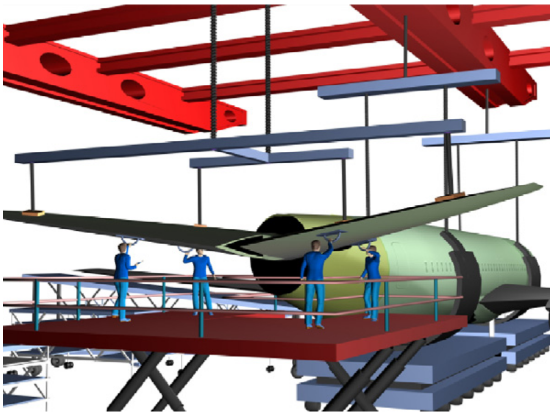


Figura 3.35: Application of cobotic devices in future human-robot-human interaction for airplane assembly (Krüger J et al. 2008).

By this, the next generation of robots will interact with human directly for cooperative manipulation, where the robot is responsible for load-bearing and precision whereas the human can contribute with sensing, intelligence and skills.

Generally the advantages of a close cooperation between human and intelligent assist systems in assembly lines build a basis for a more flexible and also more sustainable way of assembly and disassembly in the future.

3.2 A new cell production assembly system with human-robot cooperation

In manufacturing, where the wages of operators are high and the availability of expert operators remains limited, it is proving impossible to improve the efficiency of cell production assembly systems. Even novice operators are asked to achieve high levels of productivity and reliability with a diverse range of products. To satisfy this demand, the authors have developed a new cell production assembly system with human-robot cooperation. This system consists of three key technologies; parts feeding by double manipulators on a mobile base, production process information support for the operator, and safety management for cooperation between the operator and the robot.

3.2.1 Introduction

Cell production assembly systems, in which human operators manually assemble products from start to finish, play an important role in manufacturing. Several cell production assembly systems have been proposed to improve productivity and enable application to a diverse range of products with quantitative scalability.

Seki (2003) developed a production cell called the "Digital Yatai" which monitors the assembly progress and presents information about the next step in the process. Reinhart and Patron (2003) developed an augmented reality system using a semi-transparent head mount display, through which information is provided to the human operator. These studies support the operator only from information aspect, however.

Vasilash (1999) created a production cell called the "Raven Super Cell" which consists of a horseshoe-shaped fixed table and a round movable worktable. To reduce the operator's physical burden and improve the assembly precision, Hayakawa et al. (1998) employed a manipulator to grasp the component parts during the assembly process. These improved the assembly cell only in the physical support aspect.

The "Attentive Work Bench" by Sugi et al. (2005) aimed to support human operators from both an information and physical aspect. In this system, a projector is employed to provide assembly information to the operator, and self-moving trays are used to deliver parts to the operator. These devices are, however, only experimental and cannot be applied to practical manufacturing.

To maintain the competitiveness of manufacturing in those countries where wages are high, it would be advantageous if improved efficiency and cost reduction could be achieved by means of automation centered on industrial robots, with additional tasks such as parts feeding being performed by human operators. Those same human operators would also take on any complicated tasks that cannot be performed automatically by existing robots.

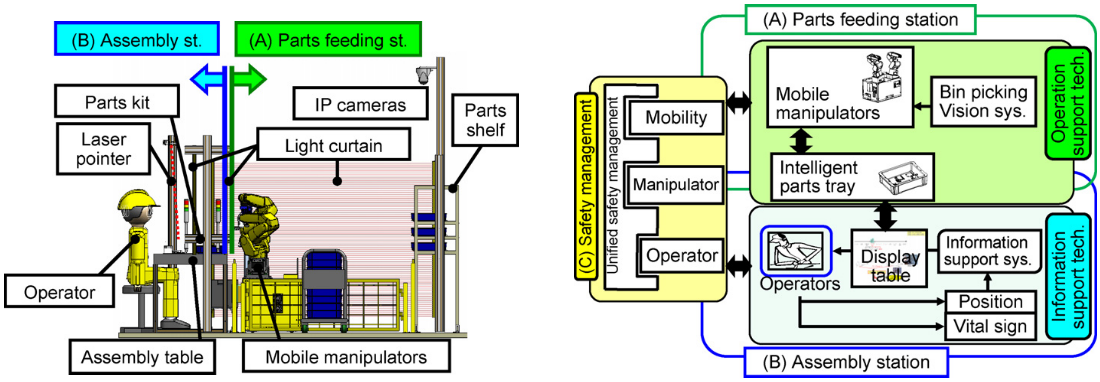
In the above-mentioned system, human-robot cooperation would be so inevitable that a safety management technology would have to be incorporated. In addition, as the present society is aging, with fewer young people, it is becoming extremely difficult to find a sufficient number of experienced operators (experts). Because of this, there is a need for an information support technology that would allow even inexperienced operators (novices) to quickly acquire the necessary skills and perform work of high quality.

The purposes of this study were as follows;

1. To develop a new cell production assembly system which will realize greater productivity and higher quality of manufacturing than is possible with conventional cell production. Achieve cost competitiveness in manufacturing that can produce a diverse range of products with quantitative scalability.
2. To develop a new operation support technology for supporting the human operators from a physical and information standpoint, centering mainly by robots.

3.2.2 System configuration of a new cell production assembly system

In this study, the authors set out to design a new cell production system, in which robots and human operators take on those tasks that are best suited to their particular characteristics. The new system has three subsystems; (A) A parts feeding station, (B) An assembly station and (C) Safety management technology. Fig. 3.36a shows the entire setup of the new cell production system, while Fig. 3.36b shows the system configuration.



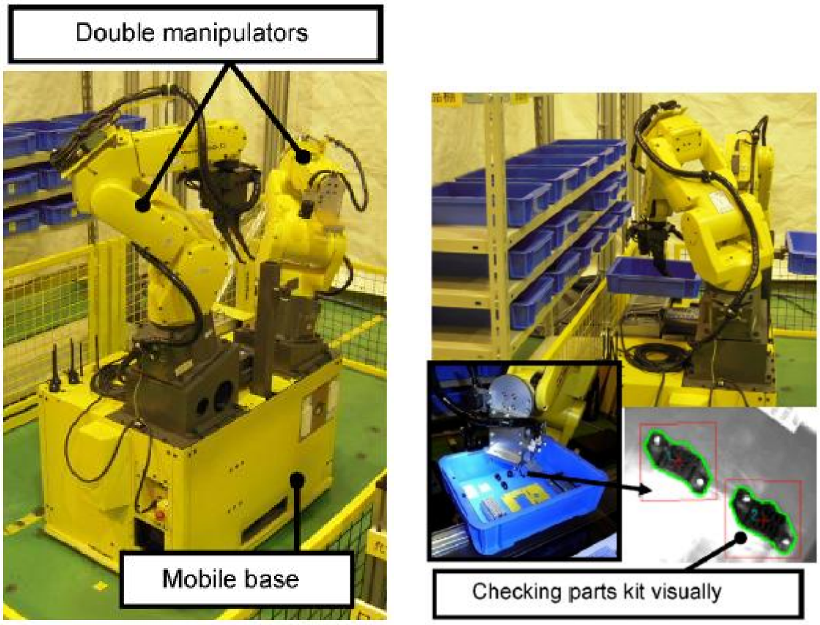
(a) *Setup*.　　(b) *System configuration*.

Figura 3.36: New cell production.

As shown in Fig. 3.36b, in (A), the parts feeding station, based on operation support technology, a robot automatically feeds all the parts necessary for assembly to the assembly station. In (B), the assembly station, based on information support technology, a human operator can concentrate on complicated work, assisted by both physical support from the robots by, for example, clamping parts as a fixture, and information support from the system. (C) Safety management technology oversees the safe interaction between stations (A) and (B), which ensures safe cooperation between the human operator and the robot. The product being assembled in this study was a cable harness with several connecters and fastener plates. The assembly takes approx. 10 min when done by an experienced operator.

3.2.2.1 Operation support technology

One of advantages of cell production assembly is the ability to modify the system layout more flexibly than would be possible with a full automatic conveyer line in order to be able to produce a diverse range of products with quantitative scalability. In this study, to enable the modification of the system layout, the authors developed a robot with double manipulators of a size equivalent to human arms for high-speed bin picking, mounted on a mobile base capable of moving in all directions and spinning, as shown in Fig. 3.37a.



(a) *Mobile manipulators.* (b) *Parts kitting.*

Figura 3.37: Mobile manipulators and parts kitting.

This robot is driven by a battery installed in the mobile base and is equipped with wireless communication systems and vision systems to compensate for any errors in the position and posture of the mobile base. In comparison with a traditional manipulator that runs on rails (typically installed in machining factories), this robot is more suitable for a cell production assembly from the viewpoint of modifying the system layout easily, simply by modifying the teaching of the robot.

The operation support technology has the following advantages;

- Full automation of parts kitting and feeding by using double manipulators on a mobile base.
- Instruction of the assembly target position by collaboration between the manipulator and a laser pointer during assembly.

In general cell production assembly, an operator is prevented from making a mistake in assembly by the preparation of a parts kit that includes all the parts necessary for assembly, which is fed to the operator. In this study, as shown in Fig. 3.37b, the use of simple additional devices and the mobile double manipulators, equipped with vision systems on their arms, enables the automation of parts feed, including the extraction of a parts bin from the parts shelves, the picking of parts from that bin, kitting of parts onto a tray, visually checking the parts in the tray, and then feeding the parts kit to the operator. This robot offers cost reduction and high reliability of parts kitting thanks to the simple additional surrounding devices such as the common part shelves and visual checking. In addition, since LED lights are installed in the vision systems, the manipulators can kit parts with high reliability, regardless of the ambient light level.

In assembling the cable harness, the authors demonstrated bin picking of nine different parts, making two kinds of parts kits and feeding them to the operator by the mobile manipulators. With this demonstration, the authors were able to confirm that this parts feeding automation system can run continuously and with high reliability.

This physical support can produce an improvement in productivity by releasing human operators from the task of obtaining parts and instead letting them concentrate on complicated assembly tasks.

On the other hand, in the assembly station, the operator assembles the parts one by one. To increase the productivity of assembly and reduce his/her burden, one of the mobile manipulators can assist the operator by clamping a part as a fixture during assembly, as shown in Fig. 3.38. In addition, since the assembly target positions are instructed step by step by the collaboration between the manipulator and the laser pointer installed in the assembly station, even novice operators can assemble parts without making mistakes.

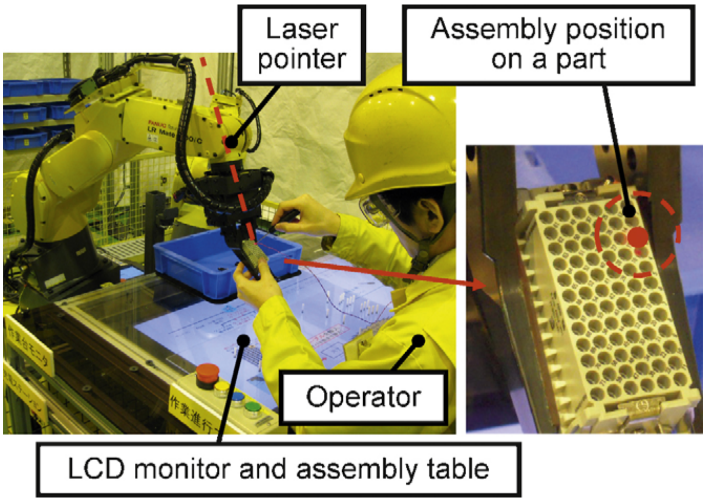


Figura 3.38: Assembly operation with assistant of manipulator.

3.2.2.2 Information support technology

In this study, the authors developed the Multi-modal Assembly Support System (MASS) that was intended to help novice operators master frequently changing assembly operations in a short time, and then go on to execute the operations with high reliability. Fig. 3.39 shows the software structure. This system has the following advantages;

- Detailed comprehensible information can be provided including multi-modal information with pictures, animation and voice by an assembly table with a horizontally built-in LCD monitor.
- The amount and degree of detail of the information can be controlled according to the skill level of the operator.

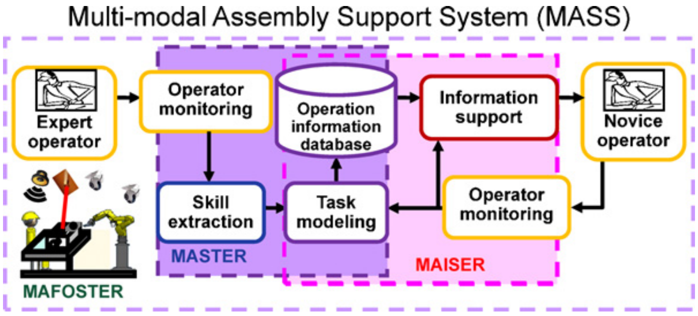


Figura 3.39: Software structure of skill transfer system and assembly information support system.

This system consists of the Multi-modal Assembly Skill TransfER (MASTER) and Multi-modal Assembly Information SupportER (MAISER), as shown in Fig. 3.39.

MASTER mainly utilizes motion capture based on visual mark tracking using IP cameras, and evaluates the correct posture and motions of assembly experts to extract the skill information from them.

MAISER provides detailed comprehensible instructions to novice operators by displaying multi-modal information about assembly operations such as text, pictures, animation and voice (Tan JTC, Duan F, et al, 2008). A new horizontal assembly table with a built-in LCD monitor, as shown in Fig. 3.38, enables operators to read the assembly instructions, step by step, without moving his/her line of sight away from the work in hand. This new assembly table can improve productivity and reduce assembly errors.

In addition, since an ID system is installed to enable the management of the skill level of individual operators, and given that the amount of information being provided can be controlled according to the skill level of the operator, this information support system can be applied widely from novices to experts.

The development of MASS has allowed even novices to execute assembly with a high degree of productivity and reliability.

3.2.2.3 Safety management technology

As mentioned in Section 3.2.2.1, in the assembly station, the high speed, high-power manipulators, used for feeding parts, share the workspace with the human operator and cooperate with him/her in automatic operation. This situation demanded the development of a new method of safety management. Recently, various methods of safety management to be applied to the cooperation between human operators and manipulators have been studied (J. Krüger, T.K. Lien, A. Verl, 2009), with some of them utilizing laser scanner technology or camera systems for 3D workspace surveillance (J. Krüger, B. Nickolay, P. Seliger, 2005). However, these safety management systems are designed to stop manipulators upon detecting the approach of human operators and not to secure the safety of the manipulators as in automatic operation in cooperation with human operators.

In this study, the authors developed the following new method of safety management for manipulators, to be applied to automatic operation in cooperation with human operators; restriction of motion speed and motion range, as checked by a software system in the robot controller, configured with two independent high reliability CPUs.

As shownin Fig. 3.40, when the human operator's workspace can be separated from that of the manipulator, the whole cell is divided into separateworkspaces by a light curtain.Onthe other hand, in the case of cooperation between the human operator and the manipulators, as in the case of automatic operation with the workspace shared between the human operator and the manipulators, the light curtain is of no use and the speed and motion range of the manipulators are restricted. The speed restriction prevents the human operator from being hit hard by the manipulators, and the motion range restriction prevents him/her from becoming trapped between the manipulators and the surrounding devices. Since the above-mentioned restrictions are overseen by two independent CPUs in the robot controller, high reliability is possible.

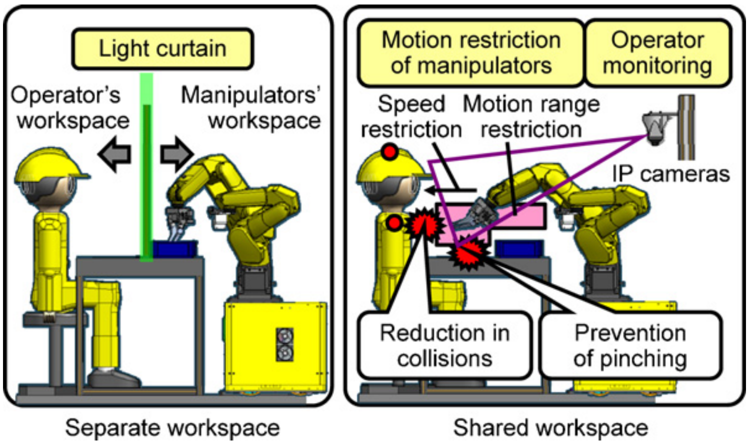


Figura 3.40: Safety management in the case of cooperation between operator and manipulators.

This new safety management enables the same manipulators to both kit parts at high speed in the parts feeding station and to assist in the assembly performed by the human operators, as in the case of automatic operation in cooperation with operators in the assembly station. If the manipulators are to shift from parts feeding and instead assist in the assembly being performed by the human operators according to the progress of the assembly, higher productivity can be achieved.

To evaluate the safety management of the entire system, including the above-mentioned method, the authors listed up 168 risks including reasonably foreseeable misuses, and set up countermeasures according to the "Three Step Method" (inherently safe design measure, safeguarding or complementary protective measure, and information for use), as defined in ISO 12100 (2003) as a risk assessment method. Since some risks have yet to be solved, the authors will develop functional safety including the monitoring of the operator by IP cameras, as shown in Fig. 3.40, in order to improve safety.

3.2.3 System performance evaluation

To evaluate the effect of the new cell production system, a group of operators was required to execute the assembly of a cable harness. In this task, operators were required to insert cables into the corresponding holes in the connector.

Two parameters were measured in the experiments; assembly time and error ratio. These two parameters were compared between conventional manual assembly cell production (Exp I) and the new cell production (Exp II). Five novice and five expert operators performed three assembly trails for both the cells.

From Fig. 3.41, the authors can see that the overall performance is better (shorter assembly time) in the new cell production (Exp II). Both the novices and the experts take almost the same time to complete the assembly, from the first trial in the case of the new cell production (shown by the dotted line). This means that the assembly can be executed in a short time even by novice operators. Comparing this with the assembly time required for conventional cell production (Exp I), the novice operators need only 50% of the time in the new cell production (Exp II). That is, the productivity is doubled. Note that the assembly time in the third trial converges to a minimum in all cases. This implies that the assembly operation is relatively easy and that a human's ability to learn is high. In other words, this system may be beneficial to situations where the product being manufactured is frequently changed.

In term of assembly quality, a 10% to 20% assembly error ratio (insertion error) was observed in conventional cell production (Exp I), while in the new cell production (Exp II) errors were totally prevented thanks to the assistance of the robot, especially the laser pointer guidance and the instruction on the assembly sequences.

According to the experimental results discussed above, the authors can conclude that the new cell production assembly system can accelerate the speed at which an operator can work, while simultaneously preventing assembly errors.

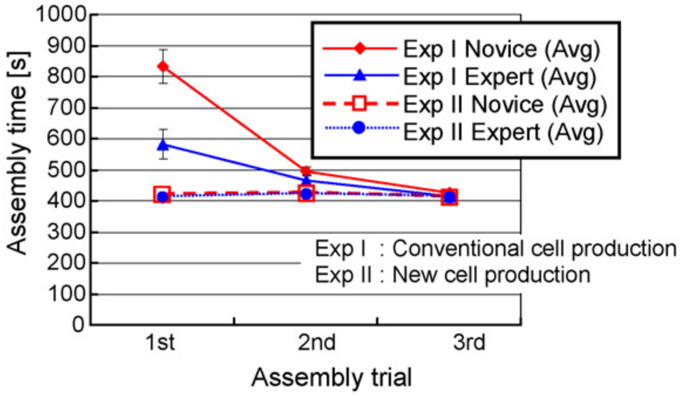


Figura 3.41: Difference in assembly time for experts and novices.

3.2.4 Conclusions and future work

In this study, the authors developed a new cell production assembly system, in which physical and information supports are provided to the human operators, reinforcing the safe cooperation with the robot while providing instructions on the operations to be performed. The safety management for the cooperation is new from the viewpoint that industrial robots can cooperate with human operators in automatic operation without stopping, which can achieve higher productivity. The authors demonstrated that, for the assembly of a cable harness, productivity with the new cell can be doubled relative to the conventional manual cell production. Furthermore, the authors proved that the assembly quality with the new cell production method can also be greatly improved because assembly errors can be almost entirely eliminated.

In addition, the new method of automatic parts kitting and feeding by the mobile manipulators allows the operators to concentrate on the assembly operations and improve productivity in comparison with conventional manual parts kitting and feeding.

This new cell production assembly system is expected to be installed in manufacturing factories in the near future. To promote the installation, the authors will make greater efforts to reduce the cost of the setup including the mobile manipulators and the safety management, and strive to improve safety even further.

Capitolo 4

RISULTATI, LAVORI FUTURI, CONCLUSIONI

CON QUESTO CAPITOLO concludiamo la tesi esponendo in primo luogo i risultati ottenuti. Successivamente vengono proposti alcuni suggerimenti per i lavori futuri, consapevoli che molto lavoro rimane da fare in merito ai sistemi di produzione ed assemblaggio flessibile. Infine vengono tratte alcune conclusioni.

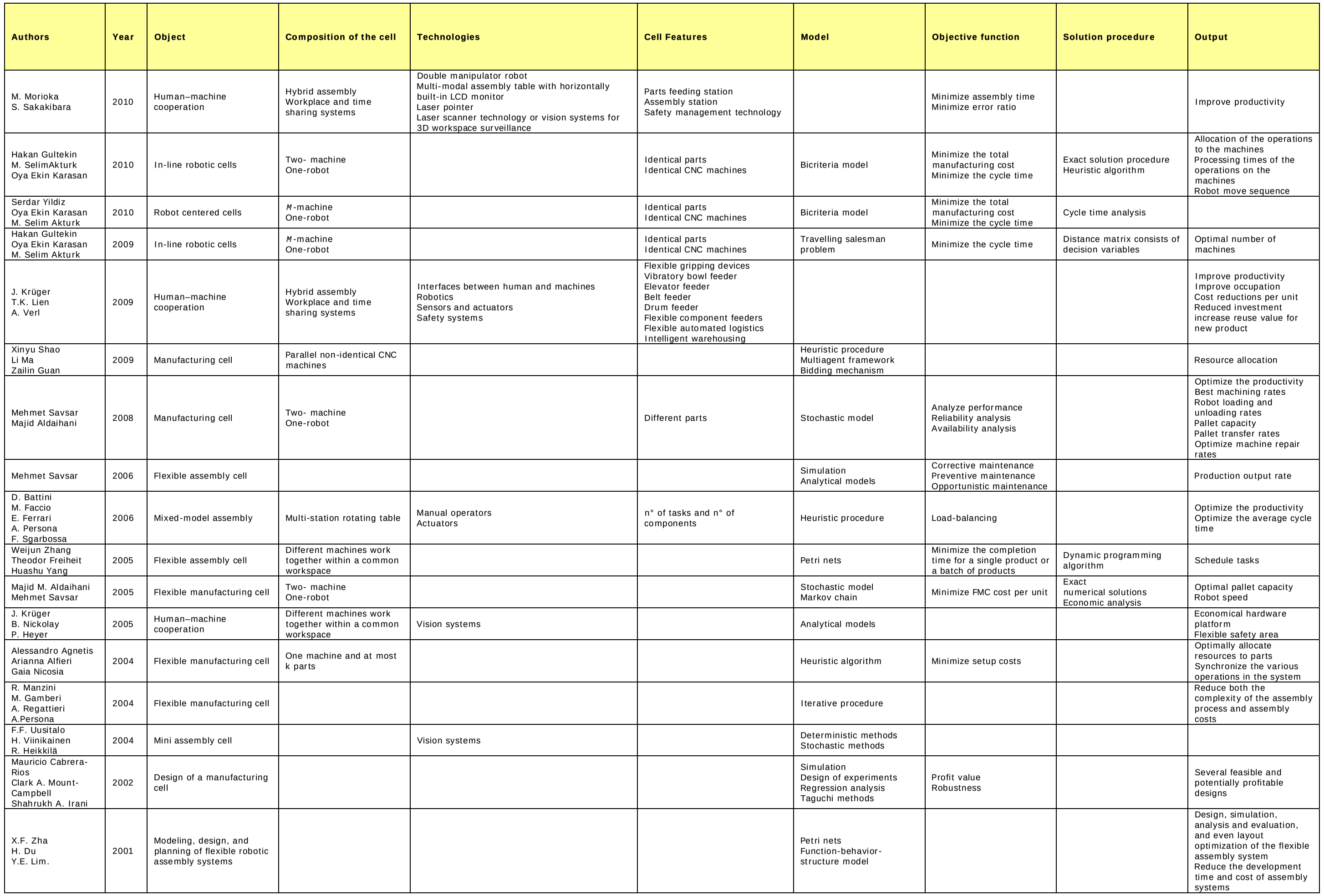
Risultati

Negli ultimi dieci anni la ricerca nel campo dei sistemi flessibili di produzione ed assemblaggio si è concentrata sia sugli aspetti di progettazione sia sugli aspetti di funzionamento, con l'obiettivo, nella maggior parte dei casi, di massimizzarne la produttività (Tabella 4.1).

Un sistema di produzione flessibile è caratterizzato da diverse macchine operatrici e diverse parti da manipolare, quindi, al fine di massimizzare la produttività (che di solito corrisponde a una minimizzazione dei costi di produzione) è necessario allocare risorse e parti in maniera ottimale sincronizzando le varie operazioni.

In pratica, l'allocazione ottimale delle risorse e i problemi di sincronizzazione, dipendono strettamente dalla specifica architettura. Questo comporta una diversa modellazione a seconda del layout considerato con la conseguente formalizzazione della funzione obiettivo.

Sono stati proposti una vasta gamma di modelli: a partire da quelli stocastici (Mehmet Savsar et al. 2008, Majid M. Aldaihani et al. 2005, F.F. Uusitalo et al. 2004), alle procedure euristiche (D. Battini et al. 2006, Xinyu Shao et al. 2005, Alessandro Agnetis et al. 2004), a quelle iterative (R. Manzini et al. 2004), ai modelli analitici (Mehmat Savsar 2006, J. Krüger et al. 2005), agli algoritmi dinamici (Weijun Zhang et al. 2005), ai modelli bi-criterio (Hacan Gultekin et al. 2010, G. Fantoni et al. 2009), al problema del commesso viaggiatore (Hacan



Authors	Year	Object	Composition of the cell	Technologies	Cell Features	Model	Objective function	Solution procedure	Output
M. Morioka S. Sakakibara	2010	Human–machine cooperation	Hybrid assembly Workplace and time sharing systems	Double manipulator robot Multi-modal assembly table with horizontally built-in LCD monitor Laser pointer Laser scanner technology or vision systems for 3D workspace surveillance	Parts feeding station Assembly station Safety management technology		Minimize assembly time Minimize error ratio		Improve productivity
Hakan Gultekin M. SelimAkturk Oya Ekin Karasan	2010	In-line robotic cells	Two- machine One-robot		Identical parts Identical CNC machines	Bicriteria model	Minimize the total manufacturing cost Minimize the cycle time	Exact solution procedure Heuristic algorithm	Allocation of the operations to the machines Processing times of the operations on the machines Robot move sequence
Serdar Yildiz Oya Ekin Karasan M. Selim Akturk	2010	Robot centered cells	M-machine One-robot		Identical parts Identical CNC machines	Bicriteria model	Minimize the total manufacturing cost Minimize the cycle time	Cycle time analysis	
Hakan Gultekin Oya Ekin Karasan M. Selim Akturk	2009	In-line robotic cells	M-machine One-robot		Identical parts Identical CNC machines	Travelling salesman problem	Minimize the cycle time	Distance matrix consists of decision variables	Optimal number of machines
J. Krüger T.K. Lien A. Verl	2009	Human–machine cooperation	Hybrid assembly Workplace and time sharing systems	Interfaces between human and machines Robotics Sensors and actuators Safety systems	Flexible gripping devices Vibratory bowl feeder Elevator feeder Belt feeder Drum feeder Flexible component feeders Flexible automated logistics Intelligent warehousing				Improve productivity Improve occupation Cost reductions per unit Reduced investment increase reuse value for new product
Xinyu Shao Li Ma Zailin Guan	2009	Manufacturing cell	Parallel non-identical CNC machines			Heuristic procedure Multiagent framework Bidding mechanism			Resource allocation
Mehmet Savsar Majid Aldaihani	2008	Manufacturing cell	Two- machine One-robot		Different parts	Stochastic model	Analyze performance Reliability analysis Availability analysis		Optimize the productivity Best machining rates Robot loading and unloading rates Pallet capacity Pallet transfer rates Optimize machine repair rates
Mehmet Savsar	2006	Flexible assembly cell				Simulation Analytical models	Corrective maintenance Preventive maintenance Opportunistic maintenance		Production output rate
D. Battini M. Faccio E. Ferrari A. Persona F. Sgarbossa	2006	Mixed-model assembly	Multi-station rotating table	Manual operators Actuators	n° of tasks and n° of components	Heuristic procedure	Load-balancing		Optimize the productivity Optimize the average cycle time
Weijun Zhang Theodor Freiheit Huashu Yang	2005	Flexible assembly cell	Different machines work together within a common workspace			Petri nets	Minimize the completion time for a single product or a batch of products	Dynamic programming algorithm	Schedule tasks
Majid M. Aldaihani Mehmet Savsar	2005	Flexible manufacturing cell	Two- machine One-robot			Stochastic model Markov chain	Minimize FMC cost per unit	Exact numerical solutions Economic analysis	Optimal pallet capacity Robot speed
J. Krüger B. Nickolay P. Heyer	2005	Human–machine cooperation	Different machines work together within a common workspace	Vision systems		Analytical models			Economical hardware platform Flexible safety area
Alessandro Agnetis Arianna Alfieri Gaia Nicosia	2004	Flexible manufacturing cell	One machine and at most k parts			Heuristic algorithm	Minimize setup costs		Optimally allocate resources to parts Synchronize the various operations in the system
R. Manzini M. Gamberi A. Regattieri A.Persona	2004	Flexible manufacturing cell				Iterative procedure			Reduce both the complexity of the assembly process and assembly costs
F.F. Uusitalo H. Viinikainen R. Heikkilä	2004	Mini assembly cell		Vision systems		Deterministic methods Stochastic methods			
Mauricio Cabrera-Rios Clark A. Mount-Campbell Shahrukh A. Irani	2002	Design of a manufacturing cell				Simulation Design of experiments Regression analysis Taguchi methods	Profit value Robustness		Several feasible and potentially profitable designs
X.F. Zha H. Du Y.E. Lim.	2001	Modeling, design, and planning of flexible robotic assembly systems				Petri nets Function-behavior-structure model			Design, simulation, analysis and evaluation, and even layout optimization of the flexible assembly system Reduce the development time and cost of assembly systems

Figura 4.1: Flexible Cell.

Gultekin et al. 2009), alle reti di Petri (Weijun Zhang et al. 2005, X. F. Zha et al. 2001), al disegno degli esperimenti unito all'analisi di regressione e al metodo di Taguci (Mauricio Cabrera-Rios et al. 2002) passando per la simulazione (Mehmat Savsar 2006, Mauricio Cabrera-Rios et al. 2002) si sono ottenute soluzioni sia esatte che approssimate. Si deve comunque sottolineare che in tutti i casi analizzati le soluzioni approssimate hanno descritto con un ottimo grado di precisione le applicazioni pratiche consentendo un notevole risparmio computazionale.

Interessanti risultano gli studi che riguardano i sistemi ibridi caratterizzati dalla cooperazione tra uomo e robot con l'obiettivo di migliorare oltre alla produttività anche la versatilità del sistema produttivo. Infatti il loro minore grado di automazione rispetto ai sistemi completamente automatizzati, ne conferisce una migliore adattabilità nel passaggio da una produzione all'altra. I sistemi ibridi rappresentano una forma di razionalizzazione, che attraverso l'integrazione delle risorse umane nel ciclo produttivo possono contribuire positivamente anche all'occupazione.

Importanti sono i risultati emersi dal punto di vista della convenienza economica. Nello studio condotto da J. Krüger et al. 2009 sono stati valutati i costi unitari di produzione in funzione delle quantità, nelle tre configurazioni: automazione ibrida, cella robotizzata e linea di trasferimento automatizzato. In base a quanto evidenziato, l'automazione ibrida grazie ai contenuti investimenti che la caratterizza, ne viene consigliato l'utilizzo in presenza anche di lotti di produzione di piccole e medie dimensioni. Basandosi sull'esempio PowerMate (Schrft RD et al 2005) sono stati valutati i costi dell'automazione ibrida attraverso il calcolo del Valore Attuale Netto dei flussi di cassa nelle configurazioni pura cella robotizzata, assemblaggio manuale ed assemblaggio ibrido, assegnando a quest'ultimo la soluzione migliore. Il caso trattato si basa su varie ipotesi, ad esempio, che tutte le alternative producono la stessa qualità e che tutte le attività possano essere eseguite sia da un robot sia da un essere umano. Inoltre gli aspetti attinenti alle malattie e alle vacanze degli operatori non sono stati presi in considerazione. Tuttavia, questo esempio mostra una forte riduzione del tempo di lavorazione nel caso di un sistema ibrido rispetto alla soluzione manuale e alla soluzione automatica. Pertanto sistemi ibridi possono risultare economicamente vantaggiosi.

Lotter e Wiendahl (2006) hanno esaminato le prestazioni dei sistemi di montaggio ibridi, che comprendono l'alimentazione e l'approvvigionamento automatico dei pezzi. Evidenziando che il tempo di tali attività non direttamente utilizzato per l'assemblaggio può essere notevolmente ridotto incrementando di fatto l'efficienza complessiva del processo di produzione. Questo tipo di montaggio ibrido è stato confrontato con l'assemblaggio completamente automatizzato per prodotti diversi. In sei dei sette casi esaminati i costi unitari di un impianto ibrido risultarono inferiori a quelli di un impianto completamente automatico.

Sulla base dell'esperienza ottenuta in compiti di assemblaggio con dispositivi di automazione intelligente (IAD), Stanley Automation stima una riduzione dei costi degli infortuni, dei costi di gestione e costi del lavoro pari al 58% sul totale.

Nello studio proposto da M. Marioca et al. nel 2010, gli autori hanno scelto di realizzare una nuova cella di produzione costituita da tre sottosistemi; (A) una stazione di alimentazione delle parti componenti, (B) una stazione di assemblaggio e (C) la tecnologia di gestione della sicurezza. Essi hanno dimostrato che, per il montaggio di un fascio di cavi, la produttività con la nuova cella può essere raddoppiata rispetto alla produzione convenzionale (cella manuale). Inoltre la qualità dell'assemblaggio con il nuovo metodo può essere notevolmente migliorata, eliminando quasi del tutto i difetti.

Ulteriori applicazioni economiche delle soluzioni ibride si potrebbero verificare in presenza di situazioni in cui l'assemblaggio non può o può essere fatto solo con alti sforzi manuali o con soluzioni complesse automatizzate.

Le tecnologie chiave che governano questi sistemi sono:

1. **Le interfacce tra l'uomo e la macchina** che garantiscono una efficace cooperazione tra le parti, si distinguono in:
    - interfacce remote come le interfacce visive, interfacce per gesti e la voce;
    - interfacce fisiche come le interfacce aptiche, display e caschi con display (HMDs), nonché sistemi di force feedback.
2. **La robotica** con:
    - I robot assistenti: dispositivi flessibili ad interazione diretta attraverso sensori, attuatori e procedure;
    - I robot di collaborazione o cobots: dispositivi meccanici su guida dotati di servomotori, dove un operatore umano fornisce forza motrice;
    - La robustezza e stabilità dell'interazione uomo-robot;
    - L'apprendimento interattivo dell'assistente robot;
    - I sistemi robotici umanoidi antropomorfi;
    - I robot portatili.
3. **I sensori e gli attuatori**. Oltre a strategie di controllo avanzato per realizzare un robot dal comportamento conforme e quindi sicuro un secondo approccio favorisce l'impiego di attuatori per garantire la sicurezza durante l'interazione uomo-robot;
4. **La gestione della sicurezza**. La coesistenza di sistemi robotici con gli esseri umani nello stesso dominio fisico/temporale, pone il problema fondamentale di garantire la sicurezza attraverso:
    - Sistemi di pre-collisione - limitazioni e controlli basati su sensori di sorveglianza dell'area di lavoro:

    - Definendo delle zone limitate in cui i bracci robotici si possono muovere (poco flessibile);
    - Utilizzando tecnologie di rilevamento scanner in grado di determinare quando un operatore entra nella zona di influenza del robot. In funzione della posizione relativa, si procede o ad un arresto di emergenza o ad un rallentamento dell'operatività;
  - Sistemi di post-collisione - sensori integrati nel robot per individuare rapidamente la collisione tra l'uomo e la macchina.

5. **L'approvvigionamento dei componenti e la logistica**. L'efficienza complessiva dei processi flessibili non dipende soltanto dal rapporto ottimale tra l'umano e l'automazione, ma anche da come i componenti sono alimentati ai luoghi di lavoro cooperativo. Poiché la cooperazione uomo-macchina ha come obiettivi una maggiore flessibilità e adattabilità, il processo di alimentazione delle parti deve essere altamente flessibile. Si è riscontrato che nelle soluzioni proposte per l'automatizzazione del sistema produttivo circa il 75% del costo totale è da imputare agli alimentatori e ai sistemi di trasporto che consentono di automatizzare la logistica della cella, mentre le apparecchiature per la produzione e il montaggio incidono per il restante 25%. La vera sfida è quindi l'alimentazione flessibile delle parti componenti. Soluzioni di automazione per l'alimentazione e la logistica esistono da lungo tempo, basta pensare alla catena di montaggio di Henry Ford per la sua automobile modello T. Ma la maggior parte di queste soluzioni sono rigide, valide per la produzione di massa. L'alimentazione automatica è risultata essere piuttosto impegnativa a causa della grande varietà di pezzi. Ancora oggi non esiste una teoria generale o metodologia per determinare la soluzione all'automazione dei componenti. Dedicheremo a tal proposito una discussione più dettagliata successivamente. La sfida della flessibilità inizia già nella fase di presa. I robot sono intrinsecamente molto flessibili, ma la loro performance è spesso limitata dalla capacità di afferrare l'oggetto che deve essere gestito. Pinze in grado di gestire la varietà di consistenza dei materiali da quelli duri a quelli molli e flosci non sono comunemente in uso nell'ambito industriale e la tecnologia in questo settore è ancora in via di sviluppo.

   Il rifornimento degli alimentatori è un'altra sfida. Il funzionamento automatico dei sistemi di montaggio richiede un flusso costante di componenti. Tradizionalmente questa sezione del sistema di produzione è stata automatizzata in misura minore, in quanto la frequenza delle operazioni è inferiore e di conseguenza può sembrare meno conveniente intervenire in quest'area. Ma anche in questa zona ci sono sviluppi tecnici che puntano verso una maggiore flessibilità di soluzioni di trasporto automatico come i nuovi veicoli a guida automatica (AGV) che integrano sistemi di navigazione au-

> tomatica svincolandoli da percorsi fissi, rendendoli di fatto più efficaci e flessibili ed applicabili ad una gamma molto più ampia di sistemi di montaggio. I sistemi di trasporto intelligenti sono un'altra importante novità. I trasportatori sono passati dai sistemi a nastro semplice con una velocità di trasporto costante ai sistemi complessi di trasporto che portano gli oggetti lungo percorsi che sono adeguati alle esigenze di un processo produttivo specifico. Sistemi frequentemente utilizzati prevedono una sorta di identificazione del pallet su cui viaggiano i componenti così da determinarne l'instradamento corretto lungo il percorso di trasporto. É quindi possibile mescolare prodotti diversi nelle diverse fasi del processo di produzione su un unico sistema di trasporto.

Un discorso a parte meritano i sistemi di alimentazione Tabella 4.2. In molte applicazione industriali l'alimentazione delle parti è affidata ai vibrotrasportatori che hanno il compito di separare i componenti stoccati alla rinfusa convogliandoli secondo un orientamento prestabilito al punto di prelievo. I vibroalimentatori sono caratterizzati da bassa velocità di processo e bassa affidabilità a causa degli inceppamenti dei componenti da orientare. A causa di questi guasti tutta la linea deve essere fermata generando dei costi elevati. Ogni vibroalimenatore è specifico per la parte da alimentare per cui è stato progettato, così come i suoi dispositivi di orientamento che devono essere adattati nel processo di installazione in modo da ottenere l'output desiderato. L'elettromagnete è stato e viene comunemente usato come mezzo per generare la vibrazione in queste apparecchiature. Tuttavia, a causa della complessità della sua struttura meccanica presenta diversi problemi, come il rumore, il movimento non lineare delle parti e così via. Per risolvere questi inconvenienti S. B. Choi et al. 2004 hanno proposto di utilizzare un piezzo attuatore per generare la vibrazione. I vantaggi del materiale piezoelettrico includono un rapido tempo di risposta, una larga frequenza di banda ed una capacità di controllo accurato. Alcuni lavori di ricerca si sono concentrati sulla modellazione della dinamica delle parti. Mentre J.A. Vilán Vilán et al. 2009 si sono limitati unicamente al regime puramente periodico, I. Han et al. 2002 hanno affrontato anche il regime caotico, valutando gli effetti che la variazione di alcuni parametri fisici del vibroalimentatore hanno sul comportamento dinamico e sulla velocità di avanzamento delle parti. È stato verificato sperimentalmente che il tasso di trasporto in regime caotico è più o meno indipendente dalle variazioni dei parametri esterni. Z. Hu et al. nel 2005 hanno esaminato l'effetto del disaccoppiamento del moto lungo gli assi x ed y per l'alimentazione di parti fragili e delicate. Il controllo separato della vibrazione permette di ottenere due vantaggi: il primo luogo si riesce a controllare meglio il moto delle parti, mantenendole in contatto con la pista vibrante anche se la velocità di avanzamento è elevata, questo si traduce in una buona protezione delle parti fragili; in secondo luogo attraverso opportuni feedback si può controllare la forma d'onda che origina la

Authors	Year	Feeder	Vibratory drive	Parts Type	Parts Size	Oriented by	Features	Analysis Tools
G. Fantoni M. Santochi	2010	Vibrator BRUSH		Delicate Fragile	Microparts	Array of microaztuator	Weight Roughnes	ANOVA
G. Reinhart M. Loy	2010	Modular feeder (Vibratory BOWL feeder and a ring system)	Electromagnets and leaf springs			Modules of the ring system		Structural mechanical model Lagrangian Equations
J.A. Vilán Vilán A. Segade Robleda P.J. García Nieto C. Casquerio Placer	2009	Vibratory bowl feeder	Electromagnetic			Standard modules	Dynamic Geometric Electromagnetic	Newton Method Spread Sheet
G.Rosati G. Boschetti A. Biondi A. Rossi	2008	Machine vision system		Metallic subassemblies	Small parts	Vision systems Anthropomorphic robot	Complex geometries	
Paul C.-P. Chao Chien-Yu Shen	2007	Piezoelectric part feeders Horizontal platform vibrated	Parallel bimorph beams Piezoelectric actuation	Screw Nuts IC components Semi-conductor industry	Small parts			Rayleigh–Ritz decomposition method Lagrange's equations Numerical simulations
Andrew Perks	2006	Machine vision system	Belt conveyor	Different material	Variable	Vision systems Robot		
Z. Hu D.F. Farson G.P. Maul	2006	Linear vibratory	Piezoelectric actuator		Microparts		De-couple the X and Y components vibratory	Control algorithm
Yung Ting Ho-Chin Jar Chung-Yi Lin Jeng-Shen Huang	2005	Meander-line structure	Bimorph piezoelectric actuators				Heavier load	
G. Fantoni M. Santochi	2005	Modular feeder	Electrostatic fields Vibrating platform	Steel Glass Plastic	Mini and Microparts	Electric field	Conductive and dielectric objects	
Z. Hu G.P. Maul D. Farson	2005	Vibratory bowl feeder	Piezoelectric actuator	Delicate parts Fragile parts	Tiny parts		De-couple the X and Y components vibratory	Force analysis One-dimensional hardware model
M.L. Tay Patrick S.K. Chua S.K. Sim Y. Gao	2005	Vibratory bowl feeder	Electromagnets	Family of similar parts	Variable	Electro-pneumatic cylinders Stepper motors Vision systems		Neural network (Back-propagation, ART2, ARTMAP)
S.B. Choi D.H.Lee	2004	Vibratory bowl feeder	Piezoceramic actuator					Modal analysis Finite element method
M. H. Jiang Patrick Chua F. L. Tan	2003	Vibratory bowl feeder	Electromagnets			Standard modules		3D simulation software
H.-P. Wiendahl A. Rybarczyk	2003	Modular design		Different material		Air streams Aerodynamic effects	Local air resistance Projected shape Center of gravity	
L. Han S.K. Tso	2003	Vibratory feeder	Electromagnets	Different material	Wide range of parts	Decoupled vibratory feeder Vision system Sensor Air jet system		
I. Han Y. Lee	2002	Vibratory bowl feeder	Electromagnets		Small engineering parts	Standard modules		Chaotic regime
N. F. Edmondson A. H.. Redford	2002	Flexible parts feeders				Anthromopic Robot Compliance device	Weight Size	
Robert-Paul Berretty Mark H. Overmars A. Frank van der Stappen.	2002	Three-dimensional generalization of conveyor belts with fences		Polyhedral parts		Pushing Tilted plates Curved tips		
Nebojsa I. Jaksic Gary P. Maul	2001	Vibratory bowl feeder	Electromagnets	Different material	Wide range of parts	Computer algorithm to supply an air jet pulse Sensor		
N.F. Edmondson A.H. Redford	2001	Belt feeder				Sensor technology Standard non-active orientation blade Method for handling cylindrical parts	Complex geometries	
Petar B. Petrović Vladimir R. Milačić Gvozden M. Dželatović	2000	Modular design	Linear vibrating Belt conveyor		Small parts	Passive and active modules		Axiomatic Design Theory
Wendy Wolfson Steven J. Gordon	1997	Flexible parts feeders			Small parts	Passive odules Vision systems Flexible manipulator	Physically robust	
G. Rosati M. Faccio A. Carli A. Rossi	2011	Proceeding: Convenience analysis and validation of a fully flexible assembly system 16th IEEE International Conference on Emerging Technologies and Factory Automation						

Figura 4.2: Techniques for flexible feeding.

vibrazione ottimizzando le performance del vibroalimentatore. M. L. Tay et al. 2005 hanno sviluppato un alimentatore convenzionale flessibile e programmabile. Con l'ausilio di un sistema di visione e di un computer, si controllano dei cilindri elettro-pneumatici e dei motori passo passo per orientare correttamente le parti componenti senza doverle respingere come avviene solitamente. Il riconoscimento dell'orientamento delle parti avviene tramite reti neurali. Questo sistema estende l'applicabilità dei vibroalimentatori convenzionali a famiglie di parti simili senza costi aggiuntivi di set-up. Interessante l'approccio di Nebojsa I. Jaksic et al. 2001 dove si descrive lo sviluppo di un modello di comportamento di una parte componente da riorientare con un getto d'aria controllato da un computer. L'algoritmo di controllo accetta il peso della parte, la geometria e il suo attuale orientamento. Dei sensori confrontano l'orientamento presente con quello voluto e l'algoritmo determina l'impulso adeguato del getto d'aria. Nel 2003 M. H. Jiang ha sviluppato un software di simulazione 3D basato su modello matematico, in grado di eseguire la simulazione dinamica del movimento di una parte componente e dell'interazione della stessa con i meccanismi di orientamento. In questo modo si riesce a valutare la bontà del progetto dell'alimentatore prima di realizzarlo fisicamente riducendo gli extra costi derivanti da errata progettazione.

Oltre agli studi sui vibroalimentatori, lavori di ricerca si sono dedicati allo studio di alimentatori modulari. G. Reinhart et al. 2010 presentano un metodo di progettazione che assicura un funzionamento ottimale attraverso l'adattamento geometrico. Il metodo si basa su un modello strutturale del sistema meccanico, che è stato derivato dalle equazioni di Lagrange. G. Fantoni ed M. Santochi nel 2005, descrivono lo sviluppo di un alimentatore per parti mini e micro basato su campi elettrostatici. La movimentazione e l'orientamento avviene grazie ad una piattaforma vibrante e ad un campo elettrico. La vibrazione viene utilizzata per ridurre le forze di attrito tra il piano ed i componenti da orientare. In aggiunta, le operazioni di set up risultano molto veloci dato che il sistema si compone di moduli standard facilmente configurabili. H.-P. Wiendahl et al. 2003 si pongono due principali obiettivi nella realizzazione del loro alimentatore modulare: flessibilità e velocità. Obiettivi che raggiungono grazie ad un approccio aerodinamico. Gli autori sottolineano che le caratteristiche della parte componente che influenzano il suo orientamento tramite il getto d'aria sono: la resistenza aerodinamica, la proiezione della forma e il centro di gravità. Nell'alimentatore proposto si utilizza un approccio composto dai seguenti passi: (i) singolarizzazione dei pezzi, (ii) preorientamento dei pezzi, (iii) orientamento finale con procedura aerodinamica, (iv) sistema di movimentazione dei pezzi. Ancora con un approccio modulare Petar B. Petrović et al. nel 2000, risolvono il problema per l'alimentazione ad alta velocità nel montaggio di piccole parti. Il sistema prevede una zona di stoccaggio, un nastro trasportatore o un piano vibrante che portano le parti nella zona seguente di orientamento composta da moduli attivi e passivi.

G. Fantoni ed M. Santochi hanno presentato nel 2010 un sistema di alimentazione basato su delle setole opportunamente inclinate. Esso consente il movimento controllato e il corretto allineamento dei diversi componenti per forma, peso e rugosità superficiale. L'alimentatore analizzato sia dal punto di vista teorico che sperimentale ha dimostrato una buona capacità di orientamento, sia in configurazione passiva (solo scivolo) sia in quella attiva (alimentatore vibrante).

Sulla base di quanto fatto nel 2005 Z. Hu et al. nel 2006 hanno applicato il disaccoppiamento della componente vibratoria ad un alimentatore lineare. È stato sviluppato un semplice ma efficace algoritmo di controllo per la gestione della vibrazione orizzontale e verticale in modo da ottenere la traiettoria voluta. Per consentire una applicazione commerciale alla ricerca è stato implementato un attuatore economico del tipo PZT.

Utilizzando due attuatori piezoelettrici alimentati da corrente alternata, Yung Ting et al. 2005 presentano un meccanismo in grado di trasportare componenti. Il modello dinamico, il movimento, la traiettoria ottimale e la velocità di avanzamento vengono studiati analiticamente e verificati sperimentalmente.

La progettazione meccatronica di un sistema di alimentazione flessibile presentata da L. Han ed S. K. Tso nel 2003 prevede: un vibroalimetatore disaccoppiato, un sistema di visone, dei sensori di spostamento, degli amplificatori di potenza il tutto supportato da un sistema informatico. I parametri di funzionamento come l'angolo di vibrazione, l'accelerazione e la differenza di fase possono essere regolati dal software online. Questo permette all'alimentatore di gestire una vasta gamma di parti senza una conversione fisica. Possono essere alimentate anche parti di materiale diverso con rendimenti sempre vicini all'ottimo. Infine il sistema di visione può individuare facilmente eventuali inceppamenti e quindi ordinare al software di invertire il senso di avanzamento risolvendo il problema.

N. F. Edmonson e A. H. Redford nel 2001 hanno presentato un alimentatore a nastro flessibile, in grado di alimentare geometrie complesse usando una tecnologia a sensore, moduli standard per l'orientamento passivo e un metodo per la gestione delle parti cilindriche. Le caratteristiche del prototipo realizzato sono: basso costo, design compatto, set-up veloce e semplice e capacità di alimentare pezzi con velocità di avanzamento tra 30 e 60 pz/minuto.

Robert Paul Berretty et al. 2002, hanno dimostrato che è possibile orientare parti componenti poliedriche asimmetriche attraverso una sequenza di spinte/urti senza l'utilizzo di sensori, indipendentemente dal loro orientamento iniziale utilizzando una mascella composta da due piani ortogonali.

Per concludere riportiamo quelli che sembrano a nostro avviso i lavori più interessanti nell'ambito dell'alimentazione flessibile delle parti componenti. La flessibilità nel rispondere alle richieste del mercato è un requisito fondamentale per i produttori che ricercano un vantaggio competitivo in un'economia globale. Prodotti sempre più differenziati con cicli di vita brevi, bassi volumi e una riduzione dei tempi di consegna al cliente, impongono un miglioramento delle performance operative. L'introduzione di un nuovo prodotto o il cambiamento di un componente, comporta grandi modifiche nel processo di automazione. Nella maggior parte dei casi si dovrà intervenire sulle apparecchiature con cui i componenti vengono alimentati alle stazioni di assemblaggio, modificandone nella migliore delle ipotesi il set-up arrivando nei casi più estremi alla completa sostituzione delle stesse. Diverse sono le soluzioni proposte, (G.Rosati et al. 2008, A. Perks 2006, F.F. Uusitalo et al. 2004, N. F. Edmondson et al. 2002, W. Wolfson et al. 1997), tutte sostanzialmente basate sulla combinazione di un sistema di visione ed un robot manipolatore. Il sistema di visione cattura l'immagine dei componenti alimentati in modo casuale, un software di riconoscimento opportunamente tarato ne individua l'esatta posizione trasmettendo le coordinate al robot. I componenti vengono di fatto alimentati direttamente alla cella di assemblaggio senza la necessità di prevedere sistemi di singolarizzazione e pick up. Questa funzionalità è di solito indicata come la visione robotica (VGR). VGR è una tecnologia in rapida crescita ed è un modo per ridurre i costi di gestione mantenendo la produzione anche nei paesi con un costo del lavoro più elevato.

Lavori futuri

La ricerca futura dovrà concentrarsi su diversi aspetti nell'assemblaggio cooperativo ibrido come la robustezza dei componenti del sistema per la sicurezza, la riduzione dei carichi ed altro al fine di estenderne il campo di applicabilità.

Una nuova sfida sarà quella di migliorare la cooperazione tra uomo e la macchina non solo per un singolo essere umano, ma anche per un gruppo di lavoratori che devono svolgere un compito comune sostenuto da una o più macchine nello stesso momento.

La stretta collaborazione tra uomo e macchina, in futuro, potrà anche cambiare il modo in cui sistemi automatizzati saranno programmati. Si può prevedere che una vasta gamma di sistemi automatizzati cinematici come i robot useranno interfacce per una efficace modalità di apprendimento sulla base di una interazione diretta con gli operatori.

L'approccio orientato all'automazione umana potrà in generale portare a una modifica dei principi di design per i robot. Oggi la progettazione dei robot industriali si focalizza sulla precisione. Il controllo tramite l'applicazione di sensori esterni è necessaria per una interazione stabile e sicura. In soluzioni a lungo termine la progettazione di robot a sicurezza intrinseca terrà conto sia della sicurezza che dell'esattezza del controllo.

Una ulteriore sfida nell'assemblaggio sarà quello di tenere traccia della quantità di pezzi in tutti i punti di stoccaggio. Questa sfida diventa molto importante quando il processo è automatizzato. Situazioni di mancanza di parti, in qualsiasi punto richiederebbe un arresto immediato delle operazioni con la necessità di un intervento manuale per ricostituire le scorte e riavviare il processo. Gli odierni sistemi ERP sono ben sviluppati per gestire la contabilità generale delle aree di stoccaggio principale, cioè materie prime, stock intermedi e prodotti finiti. Ma il livello delle scorte di una qualsiasi di queste aree non è aggiornato in tempo reale. Pur essendo disponibile la tecnologia per monitorare in tempo reale lo stato di tutti i punti di stoccaggio, non è ancor oggi disponibile sul mercato una sua implementazione commerciale.

Con riferimento alle celle costituite da macchine identiche che producono pezzi uguali servite da un robot, future linee di ricerca potrebbero generalizzare lo studio al caso di celle alimentate da diverse tipologie di pezzi servite da più robot.

Nel campo degli alimentatori di parti sicuramente gli sforzi si dovrebbero concentrare sullo sviluppo di un sistema flessibile e programmabile di alimentazione. Fortemente auspicato dal mondo industriale, questo nuovo sistema flessibile permetterebbe una riduzione dei costi di set-up attualmente affrontati ad ogni cambio di produzione. Appropriata la strada intrapresa con i sistemi VGR, i quali sfruttando l'innovazione tecnologica nel campo dei dispositivi di presa e del riconoscimento 3D, permettono di progettare un manipolatore in grado di riconoscere, afferrare e quindi porgere al meccanismo di assemblaggio la parte componente desiderata.

Conclusioni

Nella corsa degli ultimi anni, i sistemi di assemblaggio automatizzati sono stati fortemente migliorati. Il processo di assemblaggio al giorno d'oggi viene eseguito con un multiplo di flessibilità, velocità e sicurezza rispetto a quanto è stato alcuni anni fa. Ma, a differenza delle apparecchiature per il montaggio, i sistemi di alimentazione dei componenti sono stati poco modificati. I metodi esistenti di alimentazione non soddisfano completamente le esigenze dei moderni dispositivi di montaggio in termini di velocità, sicurezza e neutralità nei confronti delle varianti di produzione. Essi attirano una piccola quantità di investimenti causando al contrario un gran numero di problemi. In molti casi, le unità di alimentazione limitano la potenzialità massima di tutto il sistema, in quanto non raggiungono i tassi di approvvigionamento richiesti dalle unità di assemblaggio.

Per quanto riguarda i sistemi ibridi, da quanto emerso si può presumere che la prossima generazione di robot interagirà direttamente con gli operatori umani per la manipolazione dei prodotti. Lo stretto legame tra uomo e macchina nei sistemi di produzione cooperativo utilizzerà sempre di più i punti di forza di entrambe gli attori. In particolare i sistemi automatizzati saranno sempre più caratterizzati per la possibilità di lavorare senza interruzione, svolgendo compiti che richiedono forza e precisione il tutto con alta produttività. D'altra parte l'essere umano continuerà a fornire le incomparabili capacità senso motorie risultando ideale per la gestione delle attività complesse e manifestando la capacità di un rapido adattamento alle sequenze di un nuovo processo.

In generale i vantaggi di una stretta cooperazione tra i sistemi intelligenti di assistenza e gli operatori umani costituiranno in futuro la base per un sistema di assemblaggio e produzione più flessibile e sostenibile.

BIBLIOGRAFIA

[1] ANDREW PERKS. *Advanced vision guided robotics provide "future-proof" flexible automation*. Assembly Automation 26/3, Pages 216-220, (2006).

[2] G. BOOTHROYD. *Assembly automation and product design*. Dekker Inc., New York, (1991).

[3] G. FANTONI, M. SANTOCHI. *An analysis of cyclic scheduling problems in robot centered cells*. Computers & Operations Research, (2010).

[4] MAURICIO CABRERA-RIOS, CLARK A. MOUNT-CAMPBELL, SHAHRUKH A. IRANI. *An approach to the design of a manufacturing cell under economic considerations*. Int. J. Production Economics 78, Pages 223-237, (2002).

[5] ALESSANDRO AGNETIS, ARIANNA ALFIERI, GAIA NICOSIA. *A heuristic approach to batching and scheduling a single machine to minimize setup costs*. Computers & Industrial Engineering 46,Pages 793-802, (2004).

[6] XINYU SHAO, LI MA, ZAILIN GUAN. *A market approach to decentralized control of a manufacturing cell*. Chaos, Solitons and Fractals 39, Pages 2303-2310, (2009).

[7] G. FANTONI, M. SANTOCHI. *A modular contactless feeder for microparts*. CIRP Annals - Manufacturing Technology, Volume 54, Issue 1, Pages 23-26, (2005).

[8] M. MORIOKA, S. SAKAKIBARA. *A new cell production assembly system with human-robot cooperation*. CIRP Annals - Manufacturing Technology 59, Pages 9-12, (2010).

[9] YUNG TING, HO-CHIN JAR, CHUNG-YI LIN, JENG-SHEN HUANG. *A new type of parts feeder driven by bimorph piezo actuator*. Ultrasonics 43, Pages 566-573, (2005).

[10] RH. HOLLIER. *Automated materials handling*. Ifs Splinger Verlag, (1983).

[11] MAJID M. ALDAIHANI, MEHMET SAVSAR. *A stochastic model for the analysis of a two-machine flexible manufacturing cell*. Computers & Industrial Engineering 49, Pages 600-610, (2005).

[12] J.A. VILÁN VILÁN, A. SEGADE ROBLEDA, P.J. GARCÍA NIETO, C. CASQUEIRO PLACER. *Approximation to the dynamics of transported parts in a vibratory bowl feeder*. Mechanism and Machine Theory 44, Pages 2217-2235, (2009).

[13] HAKAN GULTEKIN, M. SELIMAKTURK, OYA EKIN KARASAN. *Bicriteria robotic operation allocation in a flexible manufacturing cell*. Computers & Operations Research, 37, Pages 779–789, (2010).

[14] I. HAN, Y. LEE. *Chaotic dynamics of repeated impacts in vibratory bowl feeders*. Journal of Sound and Vibration, Volume 249, Issue 3, Pages 529-541, (2002).

[15] J. KRÜGER, T.K. LIEN, A. VERL. *Cooperation of human and machines in assembly lines*. CIRP Annals - Manufacturing Technology 58, Pages 628-646, (2009).

[16] WENDY WOLFSON AND STEVEN J. GORDON. *Designing a parts feeding system for maximum flexibility*. Assembly Automation, Volume 17, Number 2, Pages 116-121, (1997).

[17] D. BATTINI, M. FACCIO, E. FERRARI, A. PERSONA, F. SGARBOSSA. *Design configuration for a mixed-model assembly system in case of low product demand*. Int J Adv Manuf Technol, Pages 188-200, (2006).

[18] GUNTHER REINHART, MICHAEL LOY. *Design of the optimal feeding policy in an assembly system*. Journal of Manufacturing Science and Technology, Article in Press, Corrected Proof, (2010).

[19] D. BATTINI, M. FACCIO, A. PERSONA, F. SGARBOSSA. *Design of the optimal feeding policy in an assembly system*. International Journal of Production Economics, 121, Pages 233-254, (2009).

[20] G. FANTONI, M. SANTOCHI. *Development and testing of a brush feeder*. Manufacturing Technology 59, Pages 17-20, (2010).

[21] M.L. TAY, PATRICK S.K. CHUA, S.K. SIM, Y. GAO. *Development of a flexible and programmable parts feeding system*. International Journal of Production Economics, 98, Pages 227-237, (2005).

[22] NEBOJSA I. JAKSIC, GARY P. MAUL. *Development of a model for part reorientation in vibratory bowl feeders with active air jet tooling*. Robotics and Computer Integrated Manufacturing 17, Pages 145-149, (2001).

[23] PAUL C.-P. CHAO, CHIEN-YU SHEN. *Dynamic modeling and experimental verification of a piezoelectric part feeder in a structure with parallel bimorph beams*. Ultrasonics, Volume 46, Issue 3, Pages 205-218, (2007).

[24] WEIJUN ZHANG, THEODOR FREIHEIT, HUASHU YANG. *Dynamic scheduling in flexible assembly system based on timed Petri nets model*. Robotics and Computer-Integrated Manufacturing 21, Pages 550-558, (2005).

[25] Z. HU, D.F. FARSON, G.P. MAUL. *Economic application of piezoelectric actuator in linear vibratory feeding*. Journal of Engineering Manufacture, Volume 220, Number 12, Pages 1959-1967, (2006).

[26] MEHMET SAVSAR. *Effects of maintenance policies on the productivity of flexible manufacturing cells*. Omega 34, Pages 274-282, (2006).

[27] G. REINHART, J. WERNER. *Flexible Automation for the Assembly in Motion*. CIRP Annals - Manufacturing Technology, Volume 56, Issue 1, Pages 25-28, (2007).

[28] N.F. EDMONDSON, A.H. REDFORD. *Flexible parts feeding for flexible assembly*. International Journal of Production Research, Volume 39, Number 11, Pages 2279-2294, (2001).

[29] R. MANZINI, M. GAMBER, A. REGATTIERI AND A. PERSONA. *Framework for designing a flexible cellular assembly system*. International Journal of Production Research, Volume 42, Number 17, Pages 3505-3528, (2004).

[30] N.F. EDMONDSON AND A.H. REDFORD. *Generic flexible assembly system design*. Assembly Automation, Volume 22, Number 2, Pages 139-152, (2002).

[31] X.F. ZHA, H. DU, Y.E. LIM. *Knowledge intensive Petri net framework for concurrent intelligent design of automatic assembly systems*. Robotics and Computer Integrated Manufacturing 17, Pages 379-398, (2001).

[32] J. KRÜGER, B. NICKOLAY, P. HEYER. *Image based 3D Surveillance for flexible Man-Robot-Cooperation*. CIRP Annals - Manufacturing Technology, Volume 54, Issue 1, 2005, Pages 19-22, (2005).

[33] B. LOTTER *L'automazione del montaggio*. Tecniche nuove, Milano (1992).

[34] E. FERRARI, A. PARESCHI, A. PERSONA E A. REGATTIERI. *Logistica integrata e flessibile - per i sistemi produttivi dell'industria e del terziaio*. Esculapio, Bologna (2009).

[35] L. HAN, S. K. TSO. *Mechatronic design of a flexible vibratory feeding system*. Journal of Engineering Manufacture, Volume 217, Number 6, Pages 837-842, (2003).

[36] J.J. UUSITALO, H. VIINIKAINEN AND R. HEIKKILÄ. *Mini assembly cell for the assembly of mini-sized planetary gearheads*. Assembly Automation, Volume 24, Number 1, Pages 94-101, (2004).

[37] S.B. Choi, D.H. Lee. *Modal analysis and control of a bowl parts feeder activated by piezoceramic actuators*. Journal of Sound and Vibration, 275, Pages 452-458, (2004).

[38] Mehmet Savsar, Majid Aldaihani. *Modeling of machine failures in a flexible manufacturing cell with two machines served by a robot*. Reliability Engineering and System Safety 93, Pages 1551-1562, (2008).

[39] P. B. Petrović, V. R. Milačić, G. M. Dželatović. *New Feeding System for High Speed Assembly of Small Parts*. Manufacturing Technology, Volume 49, Issue 1, Pages 9-12, (2000).

[40] A. Cerina. *Organizzazione della produzione: guida ai moderni sistemi ed alle nuove tecniche di analisi dei metodi produttivi*. Buffetti, Roma (1988).

[41] Hakan Gultekin, Oya Ekin Karasan, M. Selim Akturk. *Pure cycles in flexible robotic cells*. Computers & Operations Research, 36, Pages 329-343, (2009).

[42] H.P. Tang, T.N. Wong. *Reactive multi-agent system for assembly cell control*. Robotics and Computer-Integrated Manufacturing 21, Pages 87-98, (2005).

[43] Robert-Paul Berretty, Mark H. Overmars, A. Frank van der Stappen. *Orienting polyhedral parts by pushing*. Computational Geometry 21, Pages 21-38, (2002).

[44] G. Rosati, G. Boschetti, A. Biondi, A. Rossi. *On-line dimensional measurement of small components on the eyeglasses assembly line*. Optics and Lasersin Engineering 47, Pages 320-328, (2009).

[45] Z. HU, G. P. MAUL and D. FARSON. *Piezo actuated vibratory feeding with vibration control*. International Journal of Production Research, Vol. 45, No. 5, Pages 1089-1100, (2005).

[46] M. H. Jiang, Patrick Chua, F. L. Tan. *Simulation software for parts feeding in a vibratory bowl feeder*. International Journal of Production Research, Volume 41, Number 9, Pages 2037-2055, (2003).

[47] R. Anthony, D. Hawkins, DM. Macrì, K. Merchant. *Sistemi di controllo*. McGraw-Hill (2001).

[48] H. Rampersad. *The DFA house, Assembly Automation, vol.13, n.4*. (1993).

[49] H.-P. Wiendahl, A. Rybarczyk. *Using air streams for part feeding systems-innovative reliable solutions for orientation and transport*. Journal of Materials Processing Technology , 138, Pages 189-195, (2003).

[50] CHRIS GREEN, JEFF KREUL. *Vibratory Feeder Bowl Analysis*, (2010).

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