Cobots for the automobile assembly line

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"Machines alone do not give us mass production. Mass production is achieved by both *machines and men." –*
Henry Ford II

Abstract — Intelligent assist devices (IADs) are a new class of hybrid[1] devices for direct, physical, interaction with a human operator in shared workspaces. These devices – designed for the assembly line worker – can reduce ergonomics concerns that arise due to on-the-job physical and cognitive loading, while improving safety, quality and productivity.

Cobots, a sub-set of IADs, implement software defined *virtual guiding surfaces* while providing some amplification of human power. They exemplify the central theme of this paper – that humans are critical in many assembly operations and ergonomics tools that enable them to perform their duties are necessary.

This paper describes broad design principles for human-machine interaction in these industrial settings. Prototype industrial cobots designed for testing and validation are described. Efforts at commercializing these technologies for use in industrial settings are currently underway.

1 Why intelligent assists and cobots?

The typical automotive assembly facility has been permanently transformed by the advent of robots – harsh, unsafe, conditions have been mitigated while simultaneously freeing up workers for tasks that are more enjoyable and less stressful. Well documented transformations include the body shop, where sheet metal is welded into a structure, and the paint shop, where the vehicle structure is painted.

In sharp contrast, other areas have gone untouched for over three decades – pneumatic tools are still in vogue. The general assembly (GA) area, where the engine and cockpit sub-systems and seats and tires are integrated with the painted shell is an excellent example of such an area. Similarly, pneumatic material handling tools dominate in the warehousing industry.

The ergonomics and productivity consequences across all U.S. industries are also well documented. U.S. industries reported that in 1995 [U.S. Bureau of Labor Statistics,1997; NIOSH/Rosenstock, 1997]:

- 43% of worker sustained injuries and illnesses were due to bodily reaction and exertion;
- 62% of all illness cases were due to repeated trauma disorders; and that
- 32% of cases involving days away from work resulted from overexertion or repetitive motion.

The total cost to US industries of these and related problems is of the order of $13 to $20 billion annually. The impact on the manufacturing sector is also rather large.

IADs generally (and cobots specifically) were created to address some of the above pressing problems. General Motors has been working with Northwestern University and the University of California, Berkeley to develop these promising solutions. More recently, Ford has embarked on parallel efforts both with Northwestern University and with Fanuc Robotics[2]. In unrelated work, Oak Ridge National Laboratory [Deeter *et al*, 1997] has developed assists for munitions handling.

This paper focuses on the Northwestern/General Motors cobotics work – from a broader, industrial, perspective. (For technical details on the architecture and controls please refer to other publications listed in Section 4.) It describes the underlying motivation, design principles and developments from this industrial/academic collaboration. Section 2 describes design parameters while Section 3 addresses the drivers of the technology. Section 4 describes some prototypes that have been built to demonstrate the technology. The conclusion, in Section 5, describes our vision for the technology**.**

2 Designing assist devices for the human, the product and the process

Henry Ford's observation (top) is still very appropriate for today's General Assembly (GA) area – which has remained, from a process perspective, essentially unchanged since his time. The tooling used tends to be mechanical in nature and is primarily powered by human and pneumatic effort. Sensing and decision making are the worker's

[1] Hybrid devices jointly optimize human and machine aspects to achieve superior integration of the human's and machine's capabilities [Karwowski, Parsaei and Wilhelm, 1988].

[2] The Fanuc device will be unveiled at the RIA/ICRA workshop on Intelligent Assist Devices at the 1999 IEEE ICRA (on 5/11/99).

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responsibility. The principal reasons for not automating GA are both technical and economic. From a technological perspective, using robots for assembly in processes with high geometric dimensional variability is yet to be achieved with the reliability levels required for high volume production. Further, programming complexity grows exponentially with the number of trim options offered to the customer (e.g., leather seats, two-tone color, V6 engine, over-head console). Financially, the necessary increase in physical floor space dramatically impacts costs.

In summary, the worker – with unsurpassed sensing and processing abilities – is a critical component in the assembly process. The primary concern, then, is that of the worker's well being, given that he/she tends to tire and is susceptible to injuries resulting from cognitive and motor effort.

Manual vs. Automation vs. Hybrid automation

Faced with this information and the plethora of electro-mechanical systems available for automation, plant designers and engineers need to determine which tasks to automate. The answer, we believe, depends on the complexity of the task – as reflected by its ergonomics, the process variability and complexity and the devices available. This choice can be viewed from the perspective of efficacy, as shown in Figure 1. IADs are appropriate in situations where their capabilities (guidance and force amplification) simplify a complex task and increase the operator's effectiveness. Automation is recommended when assembly tooling is available for high volume lines.

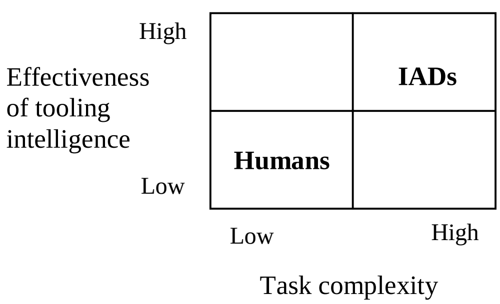

Figure 1: Where are IADs best used? (adapted from Salvendy[1988])

We will examine this model from the dual perspectives of the human operator and the product/process characteristics and attempt to converge on ideal device characteristics that best utilize the strengths of the two.

Human characteristics

Most mass production lines are designed around some human attributes: physical abilities, vocational skills, and social needs. As equal opportunity laws require that jobs be designed for most anyone in the population, devices need to be designed for a performance region. While every worker's capability to lift (static) and accelerate (dynamic) loads is different, the dynamic load (force and moment) is often the dominant concern as it leads to repetitive trauma disorders. In other cases, sideways forces (which are harder to apply than fore/aft forces) dominate.

The worker's skills (intellectual as well as hand/eye/mind coordination) directly impact the learning curve and how long it takes him to get really facile (see Figure 2). Human studies have shown that this learning curve is altered by visual, tactile, kinesthetic and auditory feedback. While simpler tasks are mastered more quickly, the learning curves for tasks of varying complexity are similar.

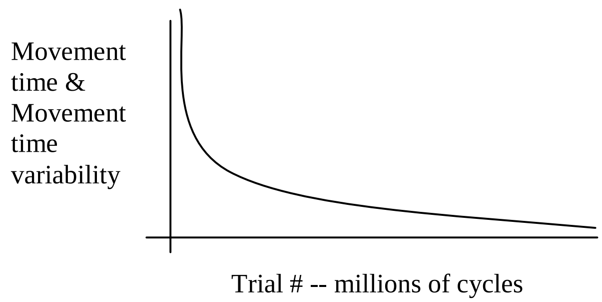

Figure 2: Effects of feedback and learning (De Jong's law)

Humans perform motions in four stages: (1) Movement to task vicinity; (2) Primary, aiming, ballastic movement; (3) Final adjustment; and (4) Finesse (quite often, tactile). Fitts' law [Fitts, 1954] states that movement time is longer for more difficult tasks – smaller and farther tasks take longer. While the operator's timing for all four stages reduces with experience, inter-operator variability persists.

Operators like to vary their routine. We have observed that they deliberately take different paths in order to converse with colleagues or to customize the path on every pass. In addition to giving them control on the task and the ability to compensate for process variation, providing for this variability also mitigates repetitive trauma disorders.

Choices slow down operators. Hick's Law states that movement time is proportional to the logarithm of the number of choices ($MT = a + b \log_2 n$, where n = the number of choices). Devices that minimize the number of choices available to the operator positively impact productivity.

Finally, we have found that getting the operator's "buy-in" is absolutely critical to the successful use of the device. As this buy-in occurs naturally if the operator is an integral part of the design and test process, we routinely include the target operators in the design team.

Product/Process characteristics

Payload (i.e., payload and tooling being handled).
The payload being manipulated is a prime driver in the design process. Its physical features such as mass, mass

distribution (i.e., inertia), payload mass/tooling mass ratio, rigidity and porosity as well as geometric features (e.g., aspect ratio and locating features) directly impact both the device and the gripper[3]. Often, in flexible plants producing multiple products on the same line (e.g., Chevrolet S-10 pickups and Blazers), loads at each station vary (e.g., three different prop-shafts of varying mass and size). A single tool that handles this set of loads is clearly attractive.

Process/product

Three factors impact the design of the device: the **product** being built (e.g., car or truck) and the features (e.g., gage holes and targets provided for location) available to the designer, the **manufacturing techniques** being used, and the **manufacturing strategy** driving decisions.

The product sets the geometric scale for all related tooling. Thus, a door loader for a compact Pontiac Grand Am has different geometric and mass characteristics than one for an Oldsmobile Aurora. Therefore, the door opening/cockpit width ratio varies, making it much harder to get the cockpit into the Grand Am's smaller door opening. Similarly, product design determines location and assembly target and the access one to them. Providing the operator with easily visible or locatable targets reduces operator effort[4] [Peacock and McCarty, 1997]. Adding guiding surfaces, such as the virtual guiding surfaces implemented in cobots, to guide the operator into the fine target simplifies the task even further. A well engineered product implementing DFx principles will, consequently, significantly reduce device complexity and costs while accelerating learning curves.

The manufacturing techniques used determine the variability/predictability of the build process – variation that the device needs to be robust to. For example, the location of the two door hinges (and, consequently, of the hinge axis) is determined by the stack-up errors during the welding of the uni-body shell. Further, as the vehicle rests imprecisely on a car conveyor as it progresses down the line, there is additional variation in the location of the hinges and the hinge axis with respect to the tool. The techniques chosen also determine factors such as part presentation (location and orientation) and proximity to the installation location. The geometry of the part as presented and as installed determines the degrees of articulation required in the tool. The proximity impacts cycle time and inefficiency in the form of non-value added work.

From a broader perspective, the manufacturing strategy chosen determines payload characteristics. A single, serial, assembly line results in many smaller components being assembled on the line while a modular assembly system results in fewer, larger and heavier, components being integrated on the line. In fact, this is the dominant trend in the industry today[5]; 70kg cockpit modules that span the width of the vehicle are the norm.

Device characteristics

A well-designed device will emphasize the strengths and de-emphasize the weaknesses of the operator while simultaneously exploiting attributes that the process and product provide. In fact, as demonstrated by the door unloader of Section 4, these electro-mechanical systems will find synergies that permit functionality that was not previously available. IADs open a new realm of performance by coupling software capabilities with electro-mechanical hardware (e.g., sensing and actuating sub-systems) to dramatically transform the nature of the operator's job. For example, the ability to recalculate – in real time – the best path in response to the operator's job-to-job preference lifts the planning burden from his shoulders.

The characteristics that we have found to be useful to focus on are the apparent payload characteristics – ones that are felt by the operator on every job cycle. Handling payload variation automatically (loaded and unloaded, or different payloads), without the operator having to consciously make decisions, is welcomed by the operators. Providing them superior response that does not slow them down determines whether the tool will be used daily. Compensating for inertia and frictional forces in addition to gravitational forces results in bio-mechanically advantageous device performance not possible with pneumatic systems. In fact, actively managing the apparent inertia that the worker feels is an excellent example of such a capability. Transforming anisotropic inertia ellipsoids into isotropic ones ensures that the device is equally sensitive to operator input on any direction. Going one step further, devices that transform their anisotropic inertia ellipsoids into anisotropic ones that are <u>matched</u> to the human's abilities render themselves even easier to use. Thus, programming the device to be more sensitive to lateral (sideways) motions than to fore aft motions matches it to the operator's capabilities (who is stronger in the fore aft direction).

A taxonomy of intelligent assist devices

Figure 3 depicts our view of how intelligent assists fit into the world of assembly tools. As IADs share the task specific aspects of traditional assists and the servo-controlled aspects of robots, they live between them in the continuum. We then divide IADs based on whether they provide force amplification or guidance. Exemplifying the former are lift

[3] Line operators often observe that "the tool is large and massive and therefore hard to maneuver and work with."

[4] For example, the wider opening of chamfered hole provides a larger "gross target" that makes it easier to hit than the smaller "fine target" of the inner hole diameter.

[5] Volkswagen and GM are experimenting with plants in which suppliers are responsible for the design of both the sub-system and the associated loading device.

assists developed by GM and UC, Berkeley[6] [Kazerooni 1996]. Passive cobots (such as the door unloader of Section 4) provide only guidance while power assisted cobots (such as the rail cobot of Section 4) provide both guidance and minimal force amplification.

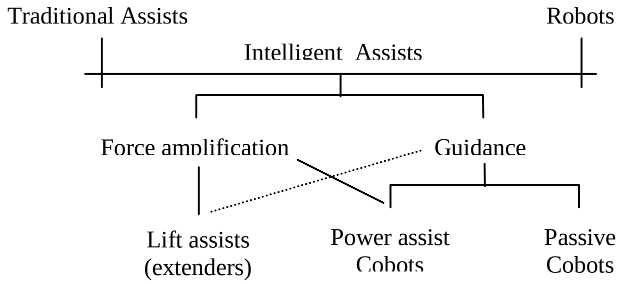

Figure 3: A taxonomy of assist devices

3 What drives this technology?

Ergonomics has driven our work in developing the IAD technology. The goal has been to develop state of the art technologies beneficial to the line worker while improving safety, quality and productivity. Cobotic enablers include:

- **Inertia management** – by handling motions to minimize the apparent inertia felt by the operator;
- **Power assistance** – by partially compensating for frictional and acceleration/deceleration forces;
- **Force amplification** – by compensating for inertial, gravitational and frictional forces, much as power steering systems amplify the driver's steering effort.

Secondary drivers, many identified after launching the project, include:

- **Simple and intuitive interfaces** – by taking over many of the operator's decisions, these sensor-based devices are very easy to use and improve productivity (in accordance with Hick's law).
- **Safety** – the close interaction between the operator and the device raises concerns about the operator's safety[7]. The controlled use of minimal energy input to the system (or, in the case of passive systems, no energy input other than the operator's) results in higher levels of safety. The rail cobot, for example, uses a 200W motor to turn the 150kg payload through a 90 degree turn with a 30cm radius at 2m/s; a non-cobotic system, in comparison, would require a 4000W motor.
- **Flexibility of the manufacturing system** – the programmability of these devices makes it possible to modify their behavior quickly. Like robots, they can – under PLC control – execute behaviors consistent with the body style in the task station. Similarly, model year change-overs becomes simpler and feasible. This ability to amortize capital costs over multiple product years permits investment in the relatively more expensive IADs.
- **Error proofing** – the on-board sensing and processing permits the designer to embed error proofing and improve product quality. By communicating with the factory's flex production scheduler via PLCs, it can ensure that a GMC Jimmy is not accidentally badged as a Chevrolet Blazer.
- **Modularity and maintainability** – Hardware and software design modularity is enabled by separating the tools into their IAD (or cobotic) parts and task dependent parts. For example, designing modular cobot wheel or CVT units permits plant personnel to swap them swiftly on the floor. In addition to replacement speed (and consequent reduction in line down time), modularity dramatically reduces the skill required by the plant's skilled trades maintenance staff. This, in turn, hastens the acceptance and implementation of the technology.
- **Tooling development efficiency** – modularity also enables improvements in tooling design. For example, sharing the same software and transmission units across two different tools minimizes design effort; the designer has only to concentrate on the task specific aspects of the tool.

4 Results – Industrial prototypes built to date

We describe, in this section, the industrial prototype cobots that we have designed and built[8] based on the principles laid out in this paper. The emphasis here is on the broader, aggregate, functionality. Technical details relating to the controls and kinematics of the devices and on implementing virtual guiding surfaces are available in focused papers [Peshkin *et al*, 1999; Wannasuphoprasit *et al*, 1998; Wannasuphoprasit *et al*, 1998]. Video footage is also available [Akella *et al*, 1999, Akella *et al*, 1998].

Prototype industrial cobots

Floor-based, passive, Cobot

The first cobot in an industrial setting is a floor-based door unloader (shown in Figure 4). This unit is now in a process validation laboratory at General Motors' Tech Center in Warren, MI and is described in Wannasuphoprasit *et al* [1998]. This passive cobotic tool takes doors off of vehicles – the first step in the GA process. It consists of a "cobot" module to control motion across the plant floor and a task specific "tooling" module to grasp and lift the door off. The

[6] The dotted line in Figure 3 indicates that guidance can be combined with force amplification.

[7] An ANSI standard, currently in development, will address these issues in greater detail.

[8] Details of prototype lift assists built will be described in a forthcoming publication.

removal process is a problematic one due to tight tolerances, highly curved body surfaces, and the need for vehicle-specific “escape trajectories” to avoid damage to any surfaces visible to customers. Additionally, the execution of this task required rotational as well as translational motion in order to locate the unloader with respect to a variable hinge axis on an imprecisely situated car moving on the line.

An important design motivation was *inertia management* – handling motions so that the apparent inertia that the operator feels is minimized. Despite the design team's concern about a loaded mass in excess of 136 kg, most operators reported finding the door unloader to be very easy to maneuver – startup force was typically less than 25N (5 pounds). This small force is due to the cobot’s low rolling friction and the use of virtual walls which minimize momentum “waste” – changes of direction are handled by steering rather than braking. The operator, consequently, does not have to supply the acceleration and deceleration forces that commonly cause fatigue and result in injuries.

Figure 4: The floor-based cobot door unloader (courtesy of General Motors Corporation)

Preliminary tests indicate that the prototype door unloader provides significant improvements in

1. **ergonomics**, by minimizing the operator's twisting and lateral forces;
2. **productivity**, by decreasing the time to master the use of the device and by reducing cycle time;
3. **quality,** by reducing the scope for human error; and
4. **safety,** because of the near-passivity of the cobot.

Efforts to quantify these improvements are on-going.

Rail-based, power-assist, Cobot

The second cobot in an industrial setting is the “railcobot” shown in Figure 5. It is installed at Ford Motor Company’s Advanced Manufacturing Technology Division. Passive overhead rail systems are very popular in automobile final assembly plants, as well as in many other applications in

Figure 5: The overhead rail-based cobot fascia loader showing the frame and traveling bridge schematic, an operator using the device, and the two CVTs used in the transmission (courtesy of the Ford Motor Company).

materials handling. A rail system may be converted into a cobot by the addition of continuously variable transmission elements (CVTs) which are adjustable under computer control, and a sensor which is used to monitor the user’s applied force. The one shown also allows the addition of a limited amount of “power assist” to help the user overcome the inherent friction of the rail system. Three benefits accrue from the conversion of a passive rail system to a cobot:

1. the inherent **friction** of the rail system can be reduced essentially to zero;
2. the **anisotropy** of the passive rail system's response to the user's forces can be eliminated. This anisotropy is due to the difference in mass of the moving parts when moving in the x and y directions.
3. **virtual surfaces** provided to guide the user's motion under computer control.

Application-specific tooling has been added to the railcobot for moving a light truck bumper from a dunnage rack to an assembly station for installation on a Ford Expedition.

5 Conclusions

Computer-controlled, electro-mechanical, intelligent assist devices are a sea change in material handling technology. The step changes in their ergonomics, productivity, quality and safety capabilities – particularly when compared to traditional pneumatic tools – are supported by initial tests. We have, in this paper, described the underlying human, process and product factors driving the design of these devices. We then discussed these principles in the context of prototypes built and tested. Quantitative tests to support qualitative and subjective results are on-going.

We believe that the promise of this synergistic integration of the operator's and electro-mechanical tooling's capabilities is significant (for example, virtual guiding surfaces and power assist). The promise includes customization of the tool's characteristics for different operators (1^{st} and 2^{nd} shift or the 95^{th} percentile male and the 35^{th} percentile female, for example), integrating error proofing into the tool for higher product quality and software-based safety to protect the operator. IADs, like robots, have the potential to dramatically impact both product and process design.

While the work has its origins in the automotive industry, the principles can be directly translated to other industries such as warehousing and parcel delivery. The IAD technology has attracted the attention of the material handling industry with several suppliers having established product commercialization teams to bring them to market.

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