

Intelligent Assist Devices in Industrial Applications: A Review

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Abstract – The state-of-the-art in Intelligent Assist Devices (IADs) is reviewed. IADs are computer-controlled tools that enable production workers to lift, move and position payloads quickly, accurately, and safely. Several examples of industrial applications are given, illustrating typical configurations and functionality, including strength amplification and virtual surfaces. The concept of human intent sensing is introduced and discussed, as are IAD safety and control considerations.

I. INTRODUCTION

Intelligent Assist Devices (IADs) are computer-controlled, servo driven tools that enable production workers to lift, move and position payloads quickly, accurately, and with ergonomic safety. IADs address the need for a solution that bridges the limitations of conventional material handling equipment and the high capital costs of robots in production environments. Factors driving the adoption of IADs include a change in workforce demographics toward older workers and more women, and a decreasing tolerance of dangerous jobs as evidenced by increasing ergonomics legislation in the US and EU. An additional factor is the growing use in auto manufacturing of pre-assembled modules that are larger, heavier and more valuable, heightening the need to avoid injuries and prevent accidental product damage.

IADs can contribute to higher productivity, improved safety and superior product quality. Since the introduction of commercial IADs, major automakers such as GM, Toyota, Honda, Ford, Visteon, Nissan, & DaimlerChrysler have purchased multiple production systems to handle instrument panels, engine blocks, struts, transmissions, and many other parts. In these rigorous plant environments, IADs have produced solid results -- 35% to 50% cost reductions in specific work cells, with payback periods as low as a month -- and are uniformly popular with operators.

IADs aim to combine the best capabilities of human manipulation with the best capabilities of machine (i.e., ro-

botic) manipulation. These two skill sets overlap very little: people are rich in body-centric sensors including 3-D vision, audition and touch, they excel at fine motion tasks such as parts assembly, and they handle many types of uncertainty with ease; robots, on the other hand, are powerful, they perform repetitive motions accurately and tirelessly, and they are easily networked into various types of information systems. Prior to the advent of IADs, it was necessary to assign manipulation tasks to either humans or robots, but not both. Automobile final assembly tasks, for example, proved too complex for cost-effective automation, and often suffered from poor worker ergonomics, high error and/or product mutilation rates, and poor productivity. IADs address these problems by allowing humans and robotic devices to work together, combining their skill sets.

II. IAD FUNCTIONALITY

IADs are single or multiple axis devices under programmable computer control that provide a variety of benefits to their human partners, including:

- Strength amplification;
- Inertia masking (i.e., reducing the starting, stopping, and turning forces, and ensuring that motions in all directions respond equally to human input);
- Guidance via virtual surfaces and paths;
- Interface to auxiliary sensors for special purposes such as weighing parts and tracking moving assembly lines;
- Interface to plant information systems for error-proofing and data logging.

IADs may be classified by their axes of motion: x and y (lateral motions), z (vertical), roll, pitch and yaw. An IAD may have only a single axis, it may have several that work independently, or it may have several that are coordinated. Figures 1-4 illustrate several examples.

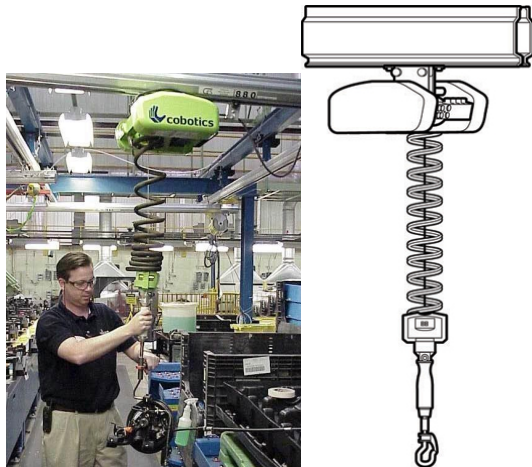


Fig. 1. Z-axis IAD.

Figure 1 shows a z-axis electric lifting and balancing unit. Z-lifts offer a number of key advances over commonly-used air balancers and hoists, including improved speed, more intuitive control, greater precision, and the ability to program semi-autonomous behaviors.

Figure 2 illustrates an Intelligent Rail System that uses servo-controlled trolleys to power the motion of the overhead crane, so that the operator need only indicate the direction he wishes to move, and the system provides the force to accelerate and decelerate the crane. Either one or two axes can be powered, according to need. In the case of a cable-suspended load, a "cable angle sensor" detects deviations of the cable from vertical and uses this information to control the trolleys. There are no pushbuttons – the IAD moves in response to the operator pushing on the payload.

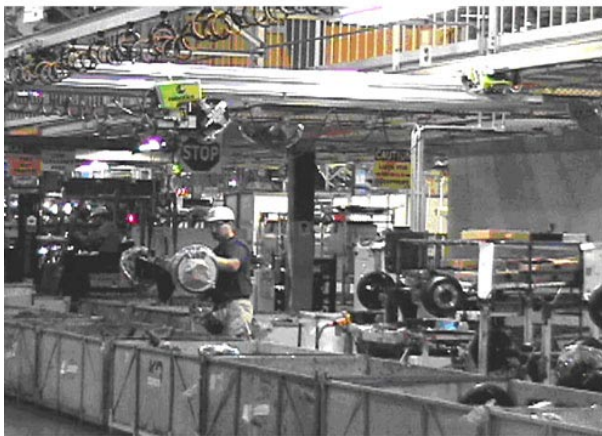


Fig. 2. Intelligent Rail System

Figure 3 illustrates a 3-axis (x, y, yaw) IAD that, due to its rigid structure, is capable of guiding human motions

via "virtual surfaces." Virtual surfaces can improve productivity and ergonomics as well. By way of analogy, consider the familiar task of drawing a straight line on a piece of paper. While possible to do freehand, the task is done much faster and better with a ruler. Virtual surfaces are like rulers, only multi-dimensional, and most importantly, user-programmable.

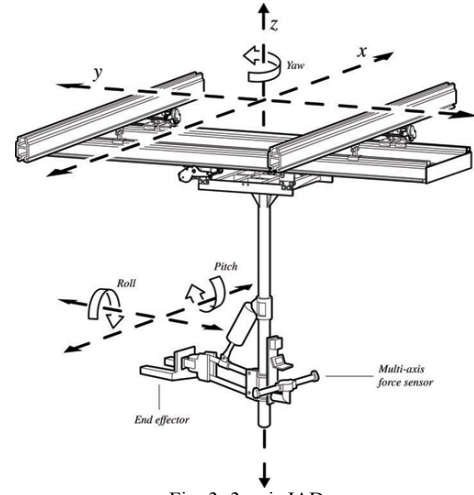


Fig. 3. 3-axis IAD

An example of a virtual surface application is loading instrument panels in vehicles, as in Figure 4. As the operator approaches the vehicle, payload motion is guided such that the instrument panel passes through a virtual window aligned with the opening in the side of the vehicle. This feature automatically adjusts the load to the proper height and prevents damage caused by accidental impact with the painted surfaces or interior trim. The system also provides line tracking, or synchronization, in order to keep the virtual window lined up with the moving vehicle.



Fig. 4. IAD for cockpit loading. This IAD is capable of semiautonomous motion.

The IAD in Figure 4 can also be programmed to perform semi-autonomous functions such as returning to a home or loading position, automatically retrieving a new part, or synchronizing with a moving assembly line. Semi-autonomous operations allow the operator to focus on value-added tasks, while the IAD takes over routine movements.

Multi-axis IADs are ideally suited for the assembly of large components such as automobile instrument panels which require both precise handling and secondary assembly operations such as inserting fasteners and connecting wire harnesses. While some elements of such tasks would benefit from the precision and speed of automation, other elements (like connecting wire harnesses) require the dexterity and intelligence of human operators.

III. INTENT SENSING

A great benefit of IADs over fully automated robots is that the excellent sensory and cognitive capabilities of the IAD's human partner are used to advantage. As a result it may be less necessary to employ high precision fixturing for the presentation of parts, or redesign of the process to reduce uncertainty. Sensing-based robotic approaches such as machine vision are also avoided (although they can be used for line tracking or positioning of an IAD).

As task and environment sensing becomes less critical, however, sensing the *intention of the human partner* becomes more critical. For physical tasks it is most natural for the human operator to express intention through manually applied forces and motions, ideally as if he/she were performing the task manually. The operator's satisfaction with the quality of the IAD depends on the sensitivity, intuitiveness, and transparency of the intent sensors and their interpretation to control the IAD.

In designing and using IADs in practice, certain desirable characteristics of intent sensors become apparent.

One of these is that it is advantageous if the operator's hands can be placed on the payload directly, rather than on control handles (e.g. force-sensing handles) at a distance from the payload. Not only does "hands-on" allow best control of payload motion, it also allows the operator to use one hand (or both intermittently) to help with other aspects of the task. Even if the operator's hands are by necessity at a distance, it is best if the handles are physically coupled to the motion of the payload, so that motion of the payload can be sensed proprioceptively.

Ideally, the operator's hands are placed directly on the payload, without even the intermediary of a sensor. When this can be achieved, it gives the operator freedom to reposition his/her hands on the payload wherever de-

sired as the payload is moved. In most cases an intervening sensor will be needed, but not in all cases. For instance, figure 2 shows Cobotics' powered crane, in which a payload is suspended from a hoist and trolleys by a wire rope (steel cable). In this instance the operator can place his/her hands directly on the payload, and the whole payload and wire rope effectively become the intent sensor. Operator forces applied to the payload cause the wire rope to deflect from vertical. These deflections are detected by an electromagnetic "cable angle sensor", the signal from which is used to drive the trolleys. Similarly, a load cell in the hoist detects the operator's vertical forces, and algorithms distinguish these forces from inertial (acceleration) forces and gravitational forces, with the residual used to control the vertical motion of the IAD. The effect of these two highly transparent sensing techniques is that the payload can be handled directly by the operator with little awareness of the IAD itself, and the payload essentially floats in space, responding to the operator's applied forces as if the payload were weightless and frictionless (but not massless).

Anyone who has tried to control a cursor on a video projector screen using a mouse, where the coordinate axes of mouse and the screen are reversed or rotated with respect to each other, knows how troublesome a lack of intuitive mapping can be. The problem is only worse in more dimensions. Interestingly, small angles (e.g. 30 degrees) of misalignment do not seem very problematic, while large angles (e.g. 90 degrees) seem to be almost insuperable, even with considerable cognitive effort. Maintaining complete correspondence of control and action axes is not always practical. When it is not, it seems that some kinds of cognitive remapping are much more intuitive than others. In conventional material handling applications such as with overhead cranes, the operator will need to look for visual landmarks such as compass coordinates (N,E,S,W) painted on the floor or a column and then determine which button corresponds to the direction they intend to go. Typically this is an iterative process where the operator pushes a button with a low probability chance of initially achieving the correct direction.

Other forms of intent sensors include multi-axis force sensing handles, and generalizations of joysticks. These may have more than two axes. Ideally the sensor itself moves with the payload and is close to the payload. Many other kinds of intent sensing can be considered, such as wireless "come hither" batons, remote joysticks that do not move with the payload, and so on. Rigorous study is needed to discover the qualities that make intent sensing effective.

IV. SAFETY

Robot safety regulations [1] insist on physical separation of people from powered-on robots in industrial applications. Most of the regulations center on how to assure this separation reliably, through fences, warnings, and interlocks. IADs, in order to work effectively with people, necessarily put people and robot-like machines in the same workspace, and the requirements for safety must be entirely rethought.

A working committee of the Robotics Industries Association has released a "draft standard for use" proposing safety regulations [2] and considerations appropriate for IADs. One of the key elements of this standard is attention to clear and unambiguous communication between operator and IAD. Modes should be few and well indicated, because accidents happen when machines move in ways people don't expect.

For instance, the standard defines "hands-on-payload mode" in distinction to "hands-on-controls mode". An IAD may at some times be capable of recognizing the operator's intention for motion expressed by pushing directly on the payload, and at other times unable to distinguish intention from noise, leaving that behavior unavailable. It is important that the operator know at all times which mode the IAD is in, and also that the IAD not enter hands-on-payload mode without an explicit command from the operator.

Clear communication in abnormal situations is equally important. An IAD must be able to distinguish an operator's force signaling intention for motion of the payload, from the kinds of force that result from an attempt to resist the motion of the IAD in an emergency. The safety standard requires over-force sensing for this purpose.

The standard describes a third mode designated "hand-off mode" in which the IAD moves without the operator's continuous instruction to move. This is a semi-autonomous mode which verges on the behavior of a traditional robot. Examples of hands-off mode are automating the return-to-home while the operator turns his/her attention to an assembly task, or line-tracking on a moving assembly line to keep the IAD in proximity to the moving workpiece, or a "go fetch" function when a worker is ready for a new part. Hands-off mode makes best use of the human operator by relieving him/her from the duty of walking the IAD from place to place. The safety standard details speeds, forces, warnings, safeguarding, and explicit enabling requirements in order to make hands-off mode safe in the presence of people.

An important difference between robot safety and IAD safety is that since people are absent from the robot's workspace, in the event of any error signal it is best to stop the robot before a person could approach and be hurt. Thus, the robot standard pays great attention to assuring the reliability of stopping circuits, requiring for instance that they use "control-reliable" relays rather than software, and so on. For IADs, working in proximity of or in contact with people, it is not necessarily the case that stopping is best. For instance, if an IAD is engaged with a moving assembly line, stopping is inferior to moving steadily with the line (or slowing as the line slows to a stop). For this reason the IAD standard does not emphasize "control reliable" hardware for stopping, except for an ultimate manually triggered emergency-stop. In most cases exceptions are better handled by software as a context-dependent safety stop.

Since IADs are at last allowing people and robots to labor together, it is amusing to look back at Isaac Asimov's "three rules of robotics" formulated in science fiction over 60 years ago:

- 1) A robot may not injure a human being, or, through inaction, allow a human being to come to harm.
- 2) A robot must obey orders given it by human beings, except where such orders would conflict with the First Law.
- 3) A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

Artificial intelligence has not lived up to Asimov's expectations, so our robots and IADs do not have the awareness and thoughtfulness these laws presume. Yet it is fascinating that Asimov captured the concept of inaction being potentially as harmful as action, as the IAD safety standard recognizes in abandoning the "stop on any fault" rule. Asimov's second law captures the importance of clear communication with and control by the human, also emphasized by the IAD safety standard.

V. CONTROL

One of the key enabling technologies for IADs is servo control. The use of servo motors and high-speed digital controls allows IADs to respond quickly to human input and other sensory inputs (e.g., line tracking signals).

Like other feedback control systems, IADs exhibit trade-offs between performance and stability. In a cable-based Intelligent Rail System, for instance, the motors actuate the overhead rail structure in response to measured cable

angle. If the operator moves the payload in a certain direction, creating a small cable angle, the overhead structure races in that same direction, attempting to keep the cable perfectly vertical. This is a fine balancing act, however. If the gains relating cable angle to motor actuation are too small, the IAD will respond sluggishly and the operator will need to exert more force than necessary to move the payload. But if the gains are too large, the result is much worse yet. The IAD over-responds and becomes unstable.

To make life even more difficult, the ideal gains depend on systems parameters such as cable length and payload inertial properties, all of which are subject to change even in the course of a single task. As a result, robust and adaptive control techniques are essential. Closely related, identification techniques are often used to measure key parameters, such as payload weight.

One example of the latter is commonly used with Z-axis lift assists. In the so-called "float mode" or "hands on payload" mode, the Z-axis lift assist perfectly balances the weight of the payload, enabling the operator to lift or lower the payload simply by grasping it and pushing in the proper direction. No controls of any sort are needed to manipulate, only to release the load. This powerful mode of operation requires that the Z-axis lift assist identify the payload weight with considerable accuracy. Moreover, to be useful in instances where parts with multiple weights or parts with unknown weight are handled, the identification must happen quickly and reliably. This requires a parameter identification scheme that can work effectively even in the presence of considerable payload acceleration. Once such scheme is outlined in the patent covering the Cobotics iLift [3].

VI. GUIDANCE

Perhaps the most exciting capability of IADs is their ability to provide guidance to operators via "virtual surfaces" such as that illustrated in Figure 5. Note that the surface is "virtual" insofar as it is defined in software, but its effects in guiding a payload are quite real and physical. As illustrated Figure 6, virtual surfaces may help to eliminate unwanted collisions (e.g., between an instrument panel and a car body). Virtual surfaces may also expedite tasks because they provide a way of avoiding the limits imposed by Fitts' Law[4]. Fitts' Law states that movement time varies inversely with the ratio of target size to movement length. Thus, people move slowly to small targets or through small openings. But, with virtual surfaces providing guidance, people may move a payload as rapidly through small openings as in free space. One further advantage of virtual surfaces is inertia management.

Curved virtual surfaces may be used to re-direct a large payload without the operator providing any forces whatsoever.

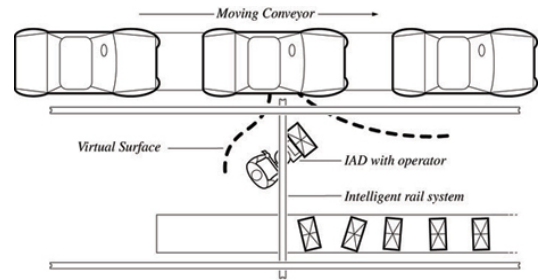


Fig. 5. Virtual surfaces

As a note, virtual surfaces may be implemented as unilateral "virtual walls" that prevent penetration but not separation, or they may be implemented as bilateral "virtual paths" that simply constrain a payload to a path through space, much like a bead on a wire. Both have their utility. Virtual walls permit greater motion variability, which many operators like. Virtual paths are easier to program and are sometimes necessary when guiding a part through a particularly tight opening. Some applications find virtual surfaces funneling down to virtual paths.

A key issue is the design of virtual surfaces. Wherever possible, straight lines or planes should be used. These are both simple to program and simple for operators to understand. In many instances, however, it is necessary to transition smoothly from one straight-line path to another. This happens, for instance, when locking onto the location of a particular vehicle on a moving line [5]. We have found that clothoids, a class of curves with smoothly varying curvature, make excellent blend paths [6]. One limitation of clothoids, however, is that they are planar curves, suitable only for blends in two degrees-of-freedom. We have developed a novel triple-clothoid path for three-dimensional blends, especially those in x-y-yaw spaces, like that of the IAD illustrated in Figure 3.

An additional benefit derived from the implementation of virtual constraints is the ability to perform error proofing tasks where an operator is prohibited from entering a certain zone in the workspace, say a particular rack of parts, based on some pre-determined set of rules programmed into the system. If the assembly operation requires "Part A", then the plant control system can send a command to the IAD which will in turn create a set of virtual surfaces that will only allow the operator to pick from "Rack A". The next request from the plant could be for "Part B", and once the previous cycle is complete a new set of constraints for "Rack B" could be implemented.

Another implementation of error proofing could be the use of automated functions such as return-to-home (RTH) where the IAD could receive a signal from the plant indicating the next part to be picked "Part A", and once the operator has completed the current task they will initiate a RTH sequence and the IAD will proceed to "Rack A", which provides the added benefit of identifying the next part to be handled without the need for the operator to manually look up the next requested part.

Another implementation of error proofing is the use of the weight measurement function to determine whether the proper part has been picked up for a particular operation.

VII. SUMMARY

IADs are increasingly being used around the world to assist industrial workers in highly specialized assembly environments such as those found in automotive manufacturing. Many of the world's leading automakers are pioneering the use of this technology in order to reach new levels of productivity, quality and safety in their assembly environments. Adoption is also beginning in other traditional material handling environments including the appliance, aerospace, converting, electronics, food, furniture, glass, packaging, printing, pharmaceutical, sheet metal, textile and warehousing industries worldwide. The technology will continue evolving to the point where intuitive human machine interaction is no longer a novelty, rather it will become a necessity

VIII. ACKNOWLEDGEMENTS

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