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THE USE OF INTERACTIVE COMPUTER VISION AND ROBOT HAND CONTROLLERS FOR ENHANCING MANUFACTURING SAFETY

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ABSTRACT

Current available robotic systems provide limited support for CAD-based model-driven visualization, sensing algorithm development and integration, and automated graphical planning systems. This paper describes ongoing work which provides the functionality necessary to apply advanced robotics to automated manufacturing and assembly operations. An interface has been built which incorporates 6-DOF tactile manipulation, displays for three dimensional graphical models, and automated tracking functions which depend on automated machine vision. A set of tools for single and multiple focal plane sensor image processing and understanding has been demonstrated which utilizes object recognition models. The resulting tool will enable sensing and planning from computationally simple graphical objects.

A synergistic interplay between human and operator vision is thus created from a programmable feedback received from the controller. This approach can be used as the basis for implementing enhanced safety in automated robotics manufacturing, assembly, repair and inspection tasks in both ground and space applications. Thus an interactive capability has been developed to match the modeled environment to the real task environment for safe and predictable task execution.

IDENTIFYING MANUFACTURING PROBLEMS

In many manufacturing facilities, the Ergonomics Coordinator and Engineering Staff have in place routine reporting mechanisms for plant production problem reporting and OSHA compliance safety reporting. On a monthly basis, issues with product quality and injury incidence are accumulated and reviewed at the plant level (**Figure 1**). These problems have been ranked and potential near-term solutions are proposed for safe and efficient operator-robot interface.

A number of reported production and safety plant problems have no immediate solution with hard automation or changes in methodology or even workcell redesign. These applications are candidates for combined operator and robotic solutions. For such

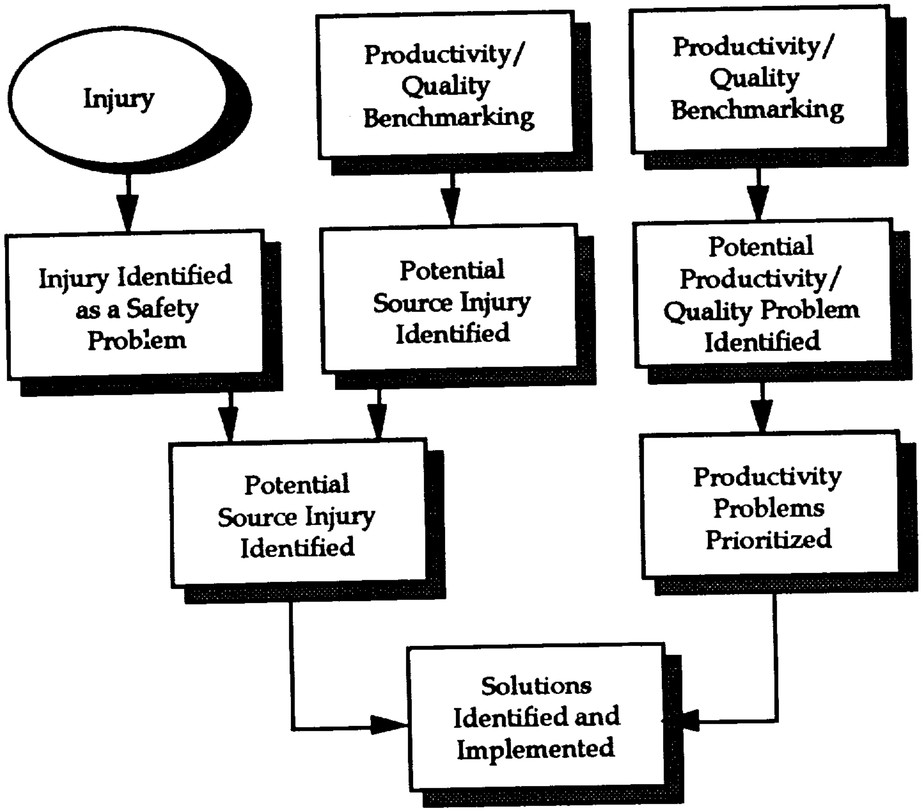

Figure 1. In-Plant Problem Identification Process

applications, a standard, rigorous methodology can be followed which consists of the following steps[1]:

(1) Identifying ergonomics problem areas which cannot be corrected through application of proven technology or job redesign -- this is performed through sanctioned plant reporting/ tracking processes outlined in Figure 1.

(2) Scoping of the problem so estimated resources can be adequately weighed against the priority of the resulting solution to plant operation (i.e. preliminary cost benefit analysis).

(3a) Analyzing relevant state of the art -- benchmarking the best of currently available job analysis/redesign methodology, automated system options, and mixed automation and human-in-the-loop methods.

(3b) Detailing the current job methodology or process to act as a baseline for improvement benchmarking

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[1] This methodology is derived from the standard Ford Motor Company "Steps to Process Improvement."

(4) Envisioning and implementing alternative teleoperated system concepts which maximize worker productivity (i.e. operation cycle times), and remain consistent with ergonomic principles.

(5) Piloting in-plant testing of most cost effective and superior system concept proposed in (3) above.

(6) Implementing the benchmarking of the system(s) pilot tested in (5) against prior manual practices as captured in step (3b). This benchmarking activity documents reduction in worker injury potential, documents any improvements in worker satisfaction and productivity, and documents any improvements in product quality if applicable.

(7) Continuous improvement of commercialization of successful human-in-the-loop technology applications. Because (5) generates an unequivocal business case, commercialization can proceed expeditiously.

Through the above process applications have been identified that can benefit from telerobotic technology. These applications are focused on making the workplace more safe for the factory worker, and at the same time improve efficiency by enhanced human-robot interaction for task generation and environment calibration. This reduction of injury aspect of this form of automation is advantageous to both worker and management. The project development process used (**Figure 2**) has been effective in getting customers acceptance and support for this technology.

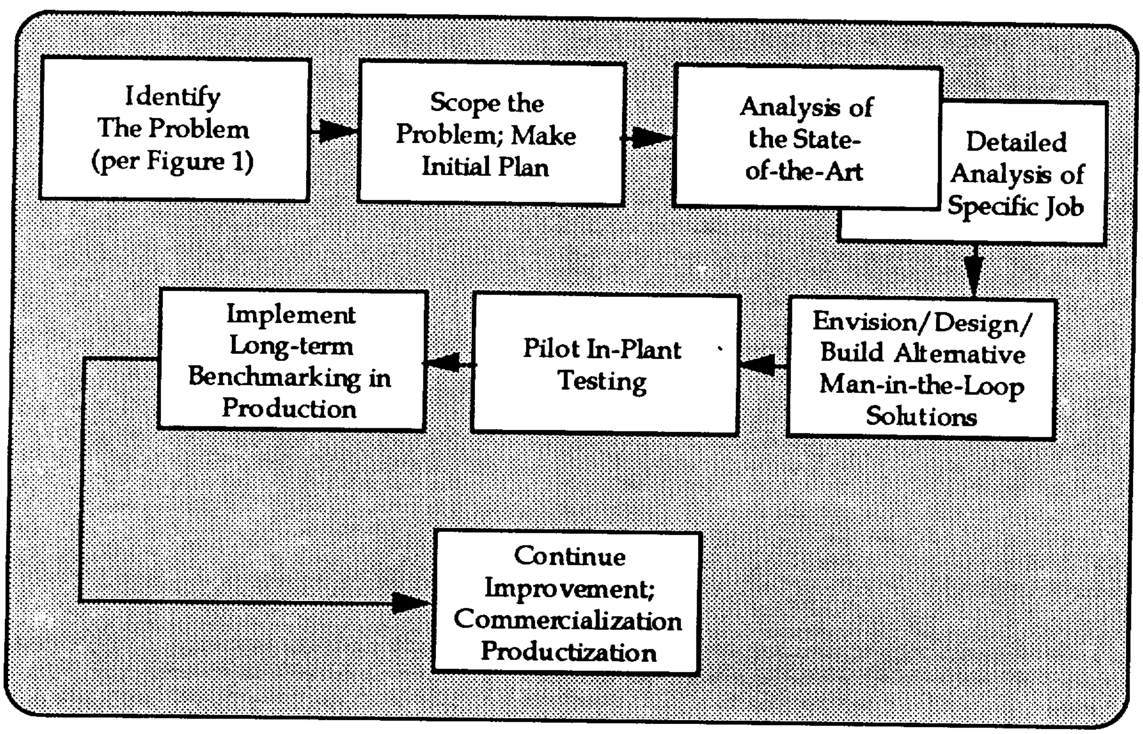

Figure 2. Technology Development Process

Telerobotics can remove a machine operator from hazardous environments by making it possible to understand, and tune operator's actions through the control interfaces to procude a specific effect at the remote machine. This added awarness is enhanced by combining computer generated visual or graphical cues with computer generated tactile/force feedback cues. Towards that goal an interactive computer vision-robot handcontroller for safe automated flexible manufacturing has been developed based on Cybernet 6-DOF force reflection handcontroller (see **Figure 3**), and advanced machine vision processing.

6 DOF HANDCONTROLLER

The PER-Force handcontroller manipulates robots or objects by "feel." Simulating a "sense of touch" by "force-reflection" with a wide motion range greatly enhances the efficiency of operations which require manipulation and dynamic control of objects in multidimensional spaces. The PER-Force handcontroller is a small backdrivable robot which moves in 6 degrees of freedom, 3 linear positions (x-, y-, z-) and 3 attitudes (roll, pitch, yaw) [1].

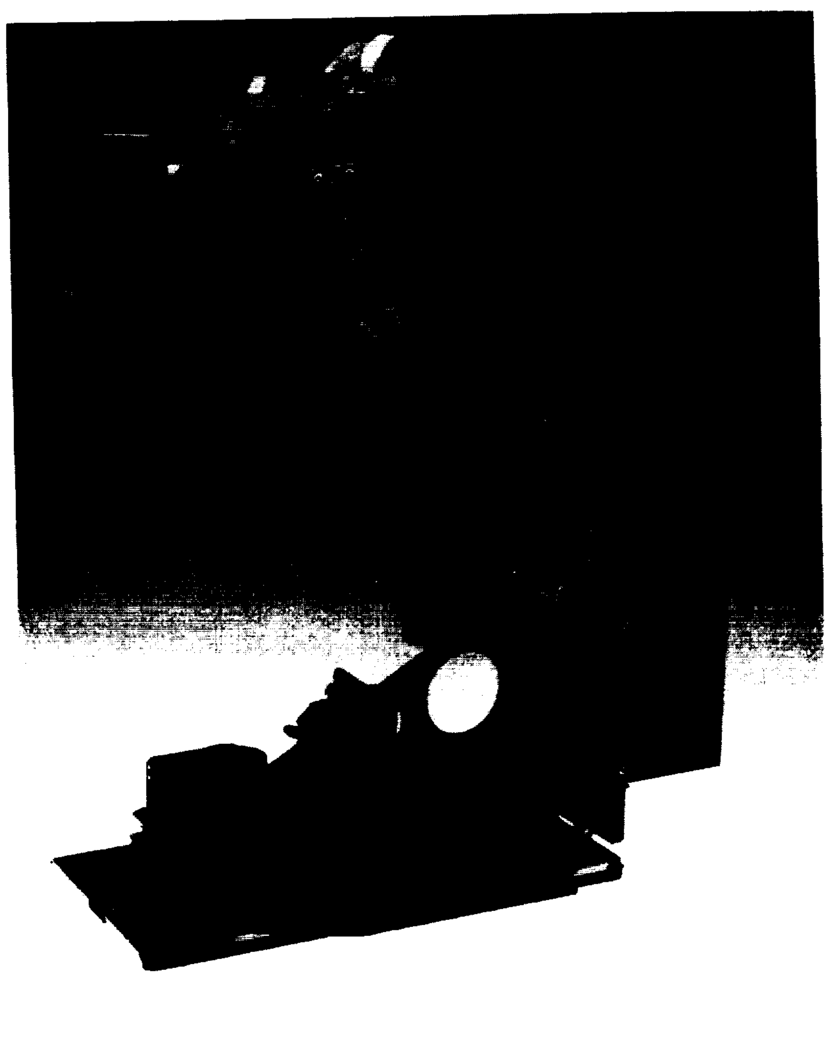

Figure 3. The Cybernet PER-Force 6 DOF Force Reflection Handcontroller

An operator can use this motorized handle to precisely position other robots or graphically displayed objects to a given location (x-, y-, z-) and tool angle (roll, pitch, yaw). This is done by a host computer or a robot control system that reads the handcontroller joint or transformed position, velocity, or force.

"Force-feedback" can be generated on each axis by the handcontroller through 6 small, brushless, DC servo motors. The six axis force-reflection output and six axis orientation and position control makes the manipulation and "feeling" of multidimensional objects or datasets extremely easy. The kinematic arrangement of the PER-Force stick is design for maximum simplicity and performance for both the electronic digital servo process and mechanical gravity compensation (**Figure 4**). The first two stages are a simple X-Y table (driven by a rack and pinion, and held in place by two parallel rails per stage). By convention X is side to side and Y is back and forth. Because these axes work parallel to gravity, no compensation is required.

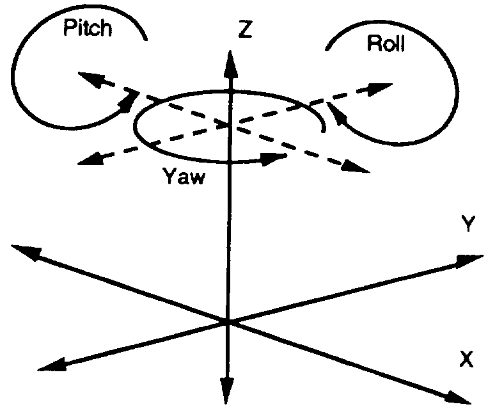

Figure 4. Handcontroller Kinematic Arrangement

The next stage is the Z axis, which is translated up and down. This axis levitates the yaw, pitch, and roll mechanisms, and the structures to which they attach. However, the Z motor and gear train themselves do not levitate (thus saving additional weight). The Z stage is gravity compensated by two constant force springs which are matched to the upper stage weight. The first revolute stage is yaw, which operates parallel to the base and therefore needs no gravity compensation. The next axis is pitch. The last axis is roll. All six axes of motion intersect at a point through the middle of the handle. We have found this to be the most comfortable pivot point for teleoperation.

The PER-Force Handcontroller is completely programmable including the time interval associated with the servo loop. Within the device, a servo shell process begins by initializing the interrupt loop data structures and linkages. After this is completed, the interrupt process runs every clock interval to provide the servo routines with a deterministic time base. In the PC-AT version, this clock interrupt is a re-programmed use of the system clock/timer.

The user initializes the desired time interval for the servo loop (shorter for crisper response -- longer to accommodate longer interrupt processing loops). The timer interrupt is skipped until enough ticks have been seen to represent this programmed interval. Then the interrupt level servo logic is executed. When the servo loop begins to run, it first collects each encoder value, computes estimates for velocity and acceleration, and then computes and option set of translations, scales, and rotations on the XYZ data and the pitch, roll, yaw data. This global transform allows the entire servo function space to be rotated, shifted, or scaled to create different force field "views".[2]

For a typical master-slave protocol, the input consists of slave positions or forces which are transformed from native slave coordinates to scaled master Cartesian coordinates (and then uses them to update gains, center locations, or forces in one or more interrupt level servo functions to create a force "feel"). Because the user actually installs pointers to their own control and/or command code, complete flexibility is available from the PER-Force servo structure (or course many useful controls are already included in the libraries). This flexibility enables the development of advanced user interfaces which use force feedback to implement new forms of machine-operator cooperative problem solving.

Towards integrating the 6-DOF handcontroller into the SGI environment, a stream module was written to generate handcontroller motion and button events for the SGI. The stram module converts a device specific data stram into an independent representation which the server interprets.

THE OPERATOR CONTROL STATION

The approach for the operator control station (OCS) is to develop a hybrid man/machine system, based on the competitive advantage of both the human and the computer, which will allow supervised control of a remote telerobot from an OCS which communicates with the telerobot over a communications channel that has a latency of several seconds and a thruput limited to several megabits per second. The operator control station [2] represents the local site of a local-remote architecture telerobotic system for remote operations. The designed architecture supports multiple local-site operator control stations with a common remote site task execution system [3] as shown in **Figure 5**. The operator interface of the local operator control station has two primary parts: perception and manipulation. Perception provides an interactive means for modeling the remote site scene. Manipulation provides interactive task description, simulation, editing, and execution. Central to the operator interface is the knowledge base which holds information on the state of the local and remote site systems and manipulation and perception data. The methodology of the local-remote system is to build and simulate manipulation and sensing commands on the local site, using a model of the robot and its environment stored in the knowledge base, which has been updated and validated with feedback sensory data.

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[2]This is analogous to changing the view port to a 3D model in model 3D graphics engines.

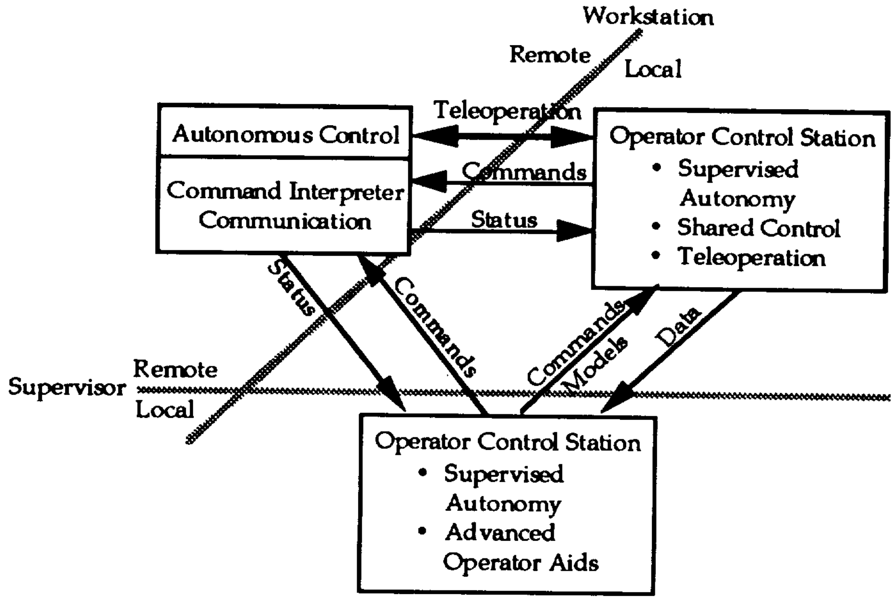

Figure 5. Local Remote Telerobot Control Architecture

The control station is hosted on a Silicon Graphics IRIS 310 VGX Power Series workstation, equipped with a 6-axis "handcontroller" input device, and with LCD shuttered glasses for 3-D stereo viewing. The local site software is written in C, utilizing X Windows, Motif, the IRIS Inventor graphics product, and a small library of X resource manager extensions called the Widget Creation Library, developed at JPL.

The interactive perception module is designed to use a combination of operator input and machine vision to refine and calibrate the model of the task environment that resides in the knowledge base. Interactive perception utilizes computer power for precision measurement, and human perception for recognition, scene segmentation, and rough location designation, where reliable and efficient computer algorithms are unavailable. To aid human perception, the system provides views from multiple video cameras, including a stereo view for depth perception. 3-D graphics is overlayed onto both the stereo video views and the monocular video views in either wireframe, transparent, or solid. The three primary functions of perception are object localization, object model editing, and camera localization. In object localization, the operator translates and operates the graphics-overlay until reasonable registration has been achieved with video images of the object from multiple viewpoints. In camera localization, the operator uses the handcontroller to adjust the graphics overlay on a video image to best register the overlay against some visible objects whose position is accurately calibrated with respect to each other. For object model editing, the operator uses the handcontroller to move a 3-D cursor in order to designate the 3-D positions of vertices, and connect them graphically with edges..

The interactive task description capability is to make task description verification, and execution as simple as possible to the operator. This is achieved by providing the operator with a library of skills which the remote manipulators can perform. Skills are generic motion types, e.g., guarded-motion, move-to-touch, hinge, slide, screw, insert etc. When parameterized, a skill becomes a command which can be sent to the remote site for execution.

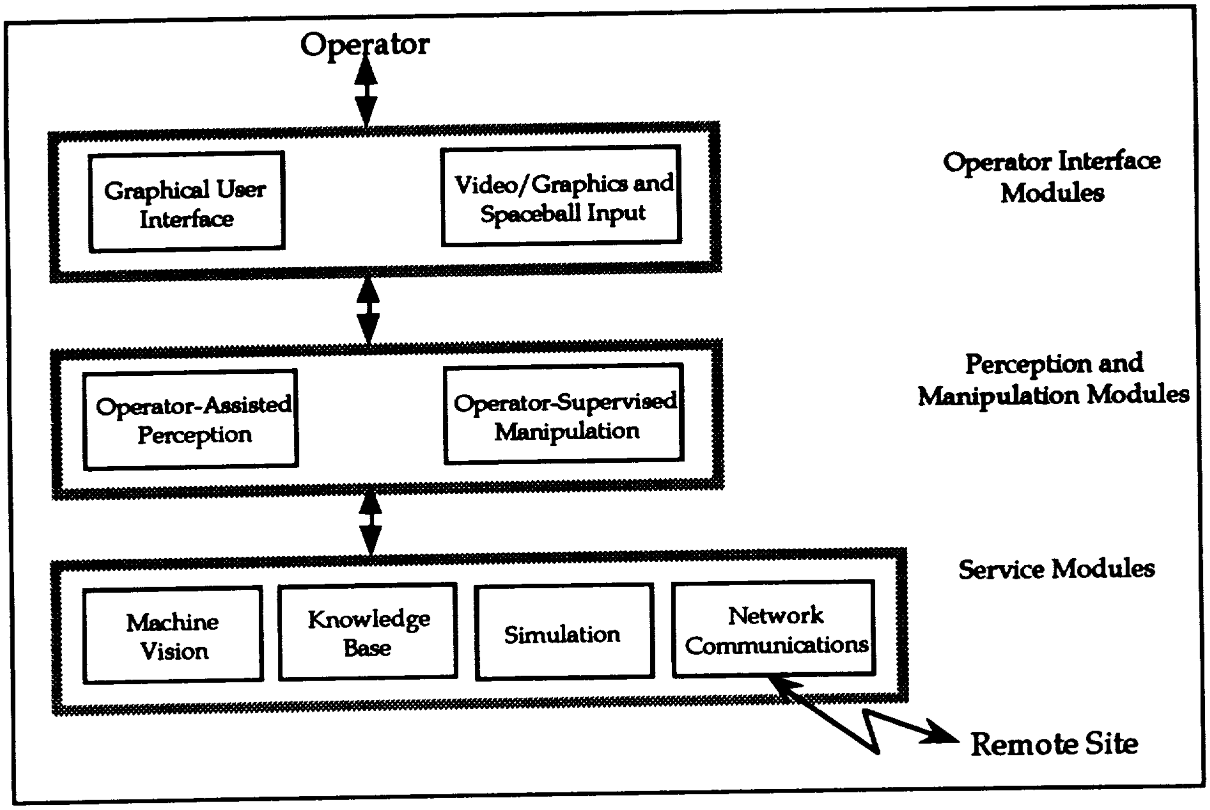

Figure 6. OCS Software Block Diagram

As shown in **Figure 6**, the software that implements the operator control station may be conceptualized in three levels. Operator interface modules directly interacting with the operator. The graphical user interface (GUI) allows the operator to command desired activities and provides high-level sequencing of subtasks, calling perception and manipulation modules as needed.

The current state of implementation of the local control station has enabled evaluation of the system's performance on several different tasks. It has been found to be an effective, convenient interface for controlling a telerobot in the presence of time delay in a semi-structured environment.

INTEGRATING THE TWO ENVIRONMENTS

The focus of our work has been directed at integrating the Per-Force into the OCS to enable rapid implementation of teleoperation environment within the manufacturing environment. Towards this end, we are developing an environment which features a 6 DOF force reflection handcontroller, contemporary CAD and graphics environments, image processing, and standardized robotic platform interfaces, to produce a 6 DOF robot controller (see **Figure 7**).

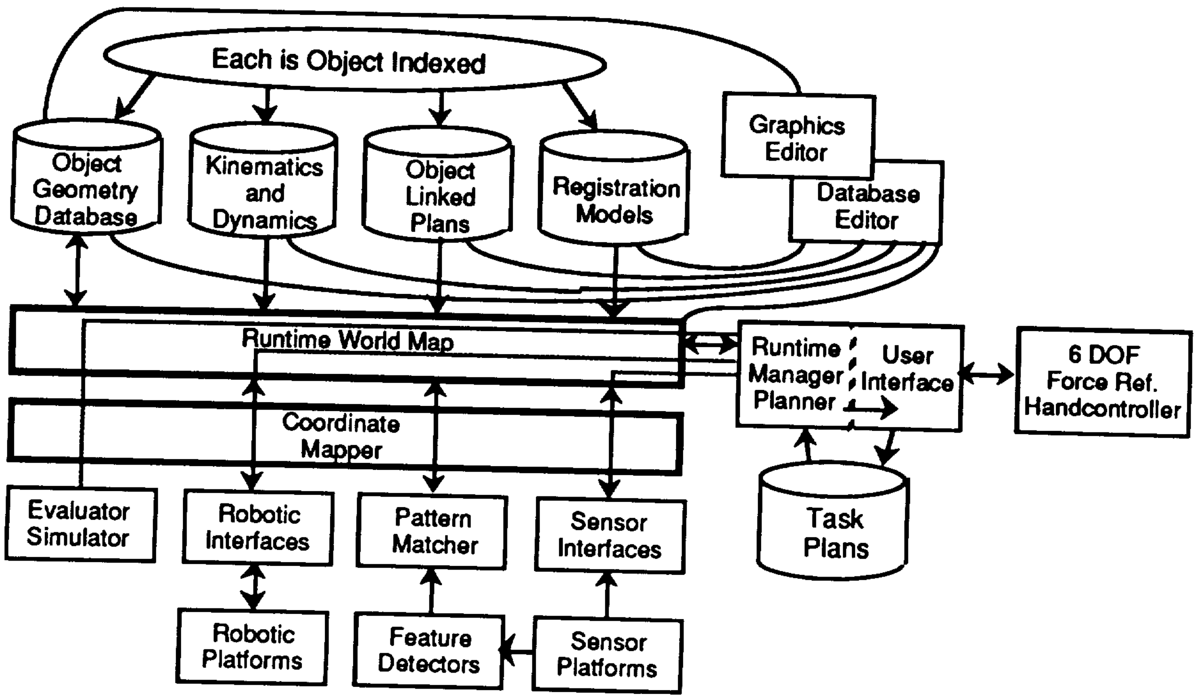

Figure 7. Combined Architecture

The development of such an environment is important because it facilitates more dynamic utilization of robots in manufacturing applications. It provides the operator with access to the geometry and physical properties of the parts to be manipulated. It bridges the gap between simulation and teleoperation. In doing so it provides an interesting vehicle for providing the human operator with supervision skills by combining human and machine vision capabilities. Within the system, object feature descriptions are linked back to the geometrical descriptions of parts (which link the feature locations to object locations and the object locations to gripping points) to enable machine vision registration of graphical part descriptions with physical sensed real-world information. Once this registration has been made, the operator can manipulate parts in a virtual reality which causes part placement within the real world.

APPLICATION TO MANUFACTURING

The process flow described above for identifying manufacturing applications has been used to identify manufacturing applications of the system under development. This process has identified several applications for this technology. One such application involves loading transmission cases within the Ford Motor Company. Currently transmission cases are delivered to the plant in large bins (nominally 4' x 4' x 7' in size - (**Figure 8**) in an unordered state and must be loaded onto kitting fixtures in a standard orientation. These cases weigh over 50 lbs and are now loaded manually, causing routine repetitive motion injuries. Standard manual lift assist devices are inconvenient and cumbersome enough that those performing this task have not adopted their consistent use.

This task is characteristic of one type of previously identified operation in which supervised teleoperation technology may be beneficial. That is, it is representative of tasks which require lifting heavier than safe loads. These tasks are still manually performed because part of the operation requires flexibility (i.e. rapid accommodation to different transmission case types) and precision placement (placement in a standard orientation onto a standard kitting fixture for insertion onto the transfer line). This semi-structured bin-picking operation has been studied for full automation, usually by computer vision-guided robotics, for many years. This approach has resisted solution because of the complexity of part motion and computer vision program changeover for each successive new part (even relatively small part design changes dictate new computer vision recognition and part gripping strategies).

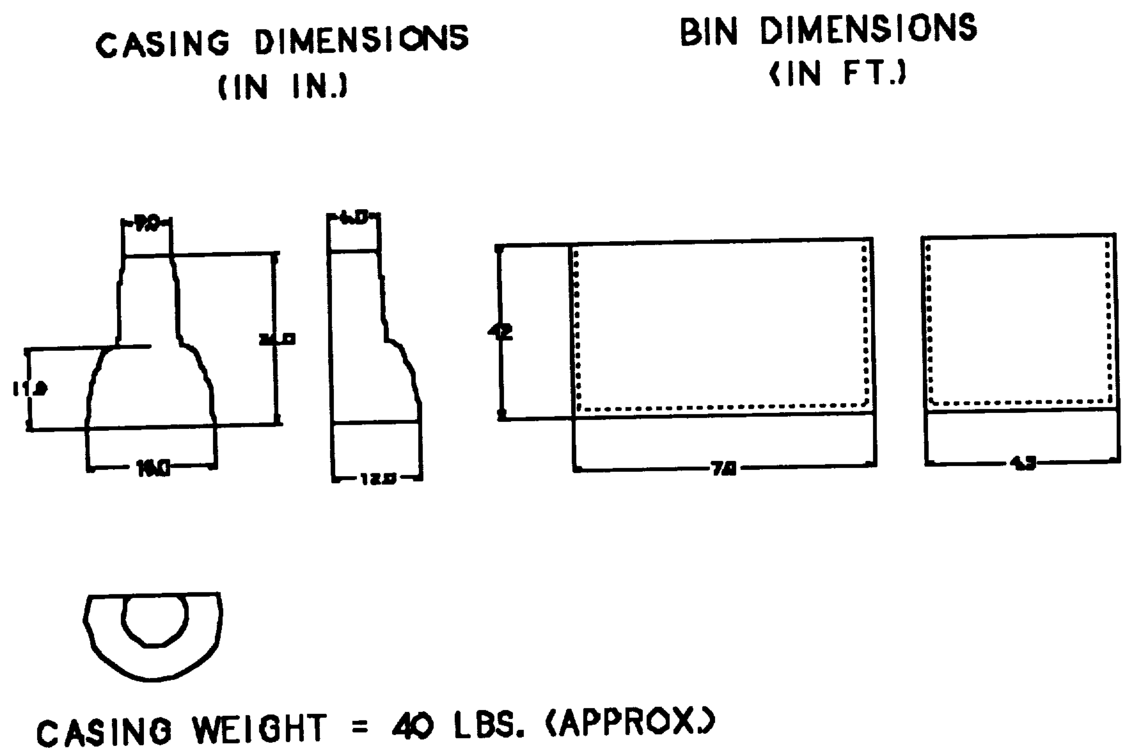

Figure 8. Transmission Cases and Their Transport Bins

Our approach combines an automated pick and place cycle robotics system with specific steps where an operator takes teleoperated control of the system. It includes an industrial robotic arm with an end effector capable of gripping and manipulating transmission cases. Control and manipulation is provided by a telerobotic force reflecting handcontroller electronically interfaced to the robot arm. Both teleoperated and automatic motions are supporting in the system to achieve both the flexibility of teleoperation coupled with the rapid cycle speed possible through automation. The alignment of transmission cases is enhanced through operator views provided by two cameras (and a graphics enhanced video viewing system). Transmission allotments are provided through a conveyor system. All moving parts/robotic elements are surrounded by safety fences. **Figure 9** illustrates such a system.

Figure 10 shows the basic architecture of the design. The physical concept is shown in **Figure 11a** (top) and **11b** (side). The unit consists of a conveyor subsystem for conveying work bins to the unloading site, a robot arm which is controlled to pick-up the transmission cases and place them on the assembly line conveyor system, and an operator control station from which operations are directed. The operator control station

Figure 9. Conceptual Layout of the Transmission Bin-Picking Cell

(**Figure 9**) consists of a telerobotic handcontroller for operator control of the robot system and a video viewing system, which allows transmission cases to be aligned for appropriate placement on the assembly transfer line.

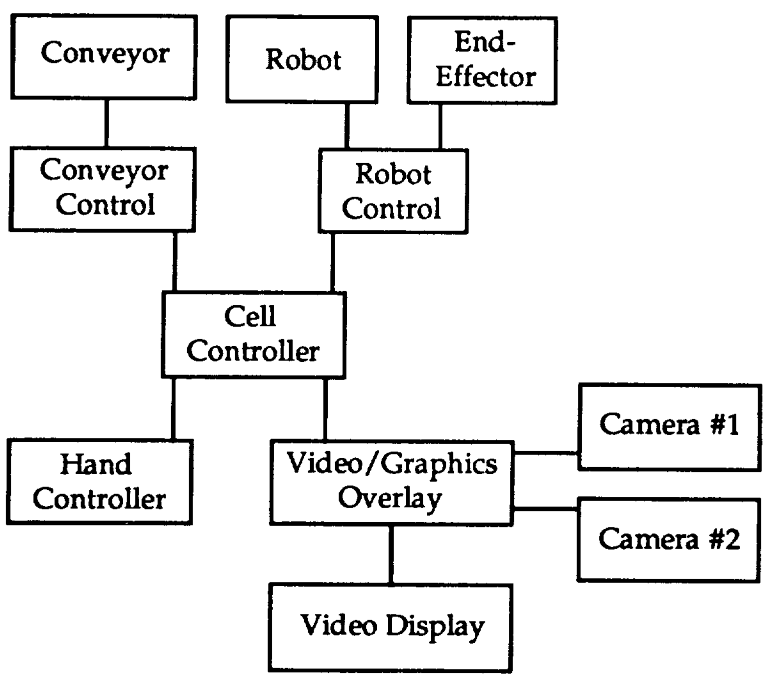

Figure 10. System architecture

As currently envisioned, a heavy duty conveyer system will be installed to convey the work bins into the work envelope. The conveyor must be designed to allow three full bins to be brought into the work envelope before the empty bins need to be removed. This system is gravity fed with safety brakes controlling the flow of the bins. The initial dimensions are estimated at 40 feet by 6.5 feet. Each bin is estimated to weigh 2000 lbs.

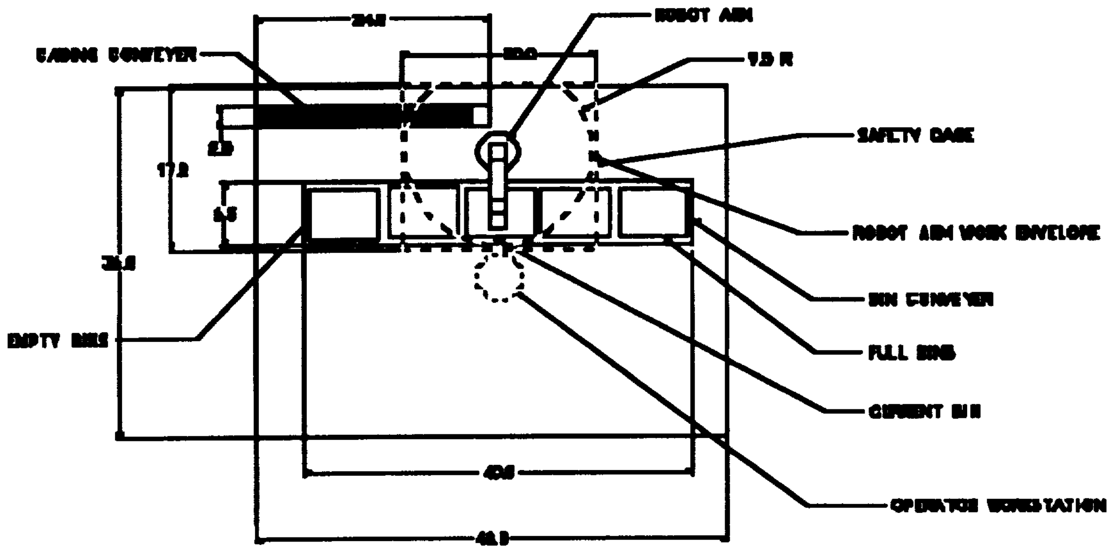

Figure 11a. Teleoperated Transmission Case Bin Picking Cell (Top)

The robotic arm which actually replaces manual lifting needs an envelope range of nominally eleven feet. A system in this size class has payload capacity of approximately 220 lbs. The arm is controlled by a combination of automated controls and a manually operated force reflecting telerobotic handcontroller. An appropriate transmission case-gripping end-effector is part of the robot system. The robot system is caged for operator safety.

The basic control interface to the operator is a telerobotic handcontroller with active force feedback. This allows the operator to have complete real-time control of the robot system position, orientation, and end-effector state (open/closed) and can allow the operator to feel robot-casing collisions and contacts. This handcontroller technology base also includes the technology of the robot system controller which acts as the cell control system, which drives conveyor, robot, and handcontroller actuators simultaneously.

A video viewing system is used to provide the operator with the visual cues necessary to properly align the transmission casing for the final placement. As currently envisioned, the operator cues the system to bring the case into a pre-specified location, within view of the video cameras, and performs manual alignment to a graphic overlaid on top of the casing video display. The cameras provide two orthogonal views which enhance the operator's ability to orient the casing prior to an automated step which places the case onto its suspension pins (on the carriers which transport the case to down stream assembly operations using the transmission conveyor system).

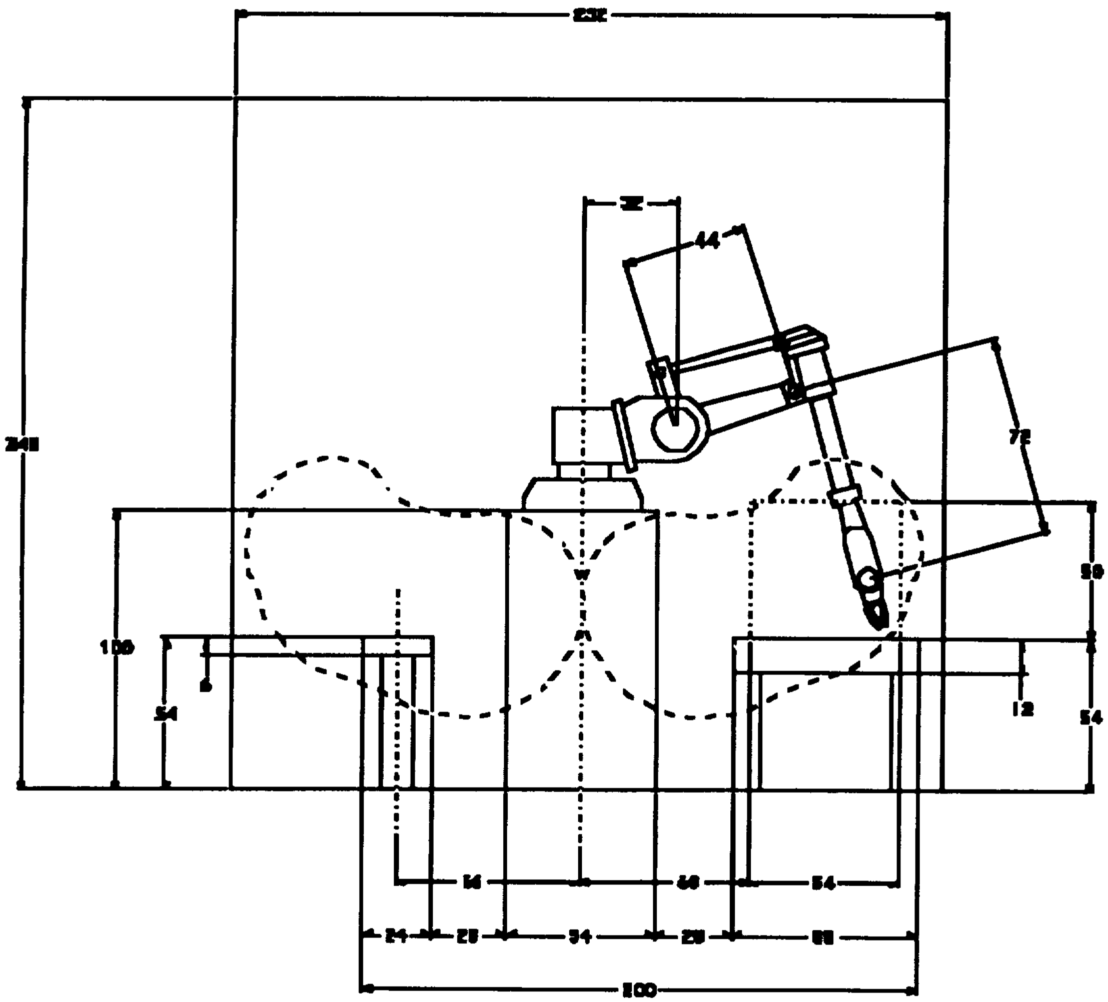

Figure 11b. Teleoperated Transmission Case Bin Picking Cell (Side)

Table 1 show a typical supervisor machine cycle for the conceptual teleoperated transmission bin-picking cell. The operator controls all actions of the robot arm through the use of a telerobotic handcontroller and control buttons. The operator is located slightly above the bin to provide direct visual contact for case grasping/gripping operations. Automation moves the robot to a location above the expected location of the next case within the bin (if this "guess" is incorrect the operator can control the robot to the correct location in the next step manually). Control is then passed to the operator (through the 6 axis handcontroller). The operator moves the robot arm to a casing using teleoperation (The operator controls the robot's end-effector by moving the handcontroller stick handle in the direction/orientation needed to mate the end-effector with the case; Tactile "feel" is provided by the stick to the operator's hand and visual cues are provide by direct viewing of the end-effector and the workpiece; End-effector grip is closed/opened through a trigger). Once the case is seized a control button is pressed which initiates a pre-programmed motion to move the transmission case to the alignment station (within view of alignment cameras). At the alignment station the operator visually aligns the case, using two cameras and a monitor (alignment is physically controlled by moving the force reflecting handcontroller to properly line up the video image of the unit with a graphics overlay target). After alignment has been

Table 1. Basic Machine Cycle: Diagram of Operations

Manual or Automated Operation	Operation Description	Operator Action Required
Automated	Robot moves to pick-up zone in bin	
Manual	If no case in the zone, operator cues system to next zone	Button Press
Automated	System passes robot control inside the zone to the operator (control is exercised through the handcontroller)	
Manual	Operator manipulates the handcontroller to place robot into gripping position around a case.	Hand Controller Operation
Manual	Operator cues end-effector gripping operation	Trigger Press
Automated	End-effector closes	
Manual	Operator cues re-grip (if grip operation failed) or automated move to the alignment viewing station (if grip is successful)	Trigger Release or Button Press
Automated	Cased is moved to the alignment viewing station	
Automated	System passes robot control to the operator for alignment	
Manual	Operator cues part flips	Button Press
Manual	Operator uses the handcontroller to make fine orientation adjustments (so that part image lines up with alignment graphics overlay)	Hand Controller Operation
Manual	Operator cues move to the transfer line conveyor fixturing	Button Press
Automated	Robot moves the case to the transfer line fixturing and places the case on the line	
Automated	Robot moves back to a pick-up zone in the bin -- operation cycles	

achieved, another switch depression initiates an automated action which places the casing on the transmission holder of the assembly line transfer conveyor.

Automated robotic pick-and-place operations can be much faster that the equivalent manual tasks, especially if the object to be manipulated is heavy for the operator. Thus, the cycle outlined decreases the loading operation time and at the same time retains manual flexibility to adapt to new transmission designs (assuming the hand-offs between man and machine are properly defined and tested).

Our system has the potential for implementing such solutions, and for quantifying capital cost and payback over an extended factory operational lifetime. The development of such applications and the verification of this payback is important to future human-in-the-loop manufacturing robotics technology.

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REFERENCES

Jacobus, H., Riggs, A. J., Jacobus, C. J., and Weinstein, Y. Implementation Issues for a Compact 6 Degree of Freedom Force Reflecting Handcontroller with Cueing of Modes. Human-Machine Interfaces for Teleoperators and Virtual Environments, Engineering Foundation, Santa Barbara, CA, March 4-9, 1990.

Bon, B., and Beahan, J., A graphics-based operator control station for local/remote telerobotics, SPIE Applications of Artificial Intelligence: Machine Vision and Robotics Conference, Orlando, FL, FL, April 1992.

Backes, P. G., Beahan, J., and Bon, B., Interactive Command Building and Sequencing for Supervised Autonomy, IEEE Int. Conf. Robotics and Automation, 1993.