World Model Registration for Effective Off- Line Programming of Robots

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ABSTRACT

This paper discusses progress in world model calibration and environmental modeling of sensory information in the context of the Off-Line Programming (OLP) project at the National Institute of Standards and Technology's (NIST) Automated Manufacturing Research Facility (AMRF). The project began in 1988 to demonstrate an integrated OLP implementation. This baseline OLP system accepts IGES CAD data, enables graphical simulation of objects and devices and produces VAL II robot trajectories. The robot trajectories, however, are based on a world model that is inherently inaccurate. A basic OLP system and most existing commercial OLP systems, therefore, are most effective only as a prototyping tool. Consequently, we are now developing our OLP system into a production tool for generating robust robot control programs. We recently completed work on world model calibration and environmental modeling of force and torque in an attempt to improve world model registration of the real world. Environmental modeling of other sensory input, such as vision, is continuing. The eventual integration of an advanced sensory interactive controller will enable off-line programming of sensor servoing to compensate for inherent world model inaccuracies and real world changes.

Keywords: robot programming, world model, off-line programming, sensory simulation, calibration, environmental model

I. INTRODUCTION

An Off-Line Programming (OLP) system provides a simulation of the real world for programming robotic workcells without the use of the real workcell. OLP of industrial robots potentially is very beneficial in improving the safety and cost-effectiveness of robotic workcells. Using OLP improves human safety by minimizing physical interaction between the operator and a powered robotic workcell. OLP also protects equipment by using simulations to check for robot programming errors that might otherwise have catastrophic results. In addition, off-line generated programs reduce robot down time which ordinarily occurs when programs are generated using the teach-pendant method. OLP, therefore, minimizes robot downtime both during and after robot programming, thus achieving significant economic benefits.

OLP systems are recognized as very useful for fast prototyping and debugging of complex robotic workcells and several commercial systems are available for that purpose [1]. However, OLP applications rarely produce the final robot control programs. Despite the significant benefits of using OLP as a production tool, OLP largely remains a prototyping tool. Therefore, our research is focused on typical OLP deficiencies. We have implemented a generic integrated OLP system with an emphasis on well known integration issues [2]. The baseline OLP world model, however, is not adequate for robust robot programming. The second and current phase of the project involves enhancing the effectiveness and functionality of the basic OLP system by implementing calibration and force/torque simulations.

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An OLP system was implemented at the Cleaning and Deburring Workstation (CDWS) in the AMRF [3]. The CDWS, shown in figure 1, consists of two robots for deburring, buffing and cleaning of machined parts [4]. The OLP project involves programming the Unimate 2000 robot for buffing parts. Both the Unimate and the Puma 760 robots perform part handling to and from the supply trays, deburring vise and washer/dryer. In addition the Puma 760 performs deburring operations. The workcell control scheme allows for concurrent tasks providing that they do not lead to a collision. An Automated Guided Vehicle (AGV) delivers and retrieves parts between workcells and the material buffering system. The goal is to program off-line the gross and, more importantly, fine motions of the Unimate 2000 buffing process. While the application area is very specific, the intent for the project is to develop generic capabilities of OLP which are transferable to any robot programming task [5]. In fact, this generic OLP technology is being applied to a new composites manufacturing workstation now under development in the AMRF.

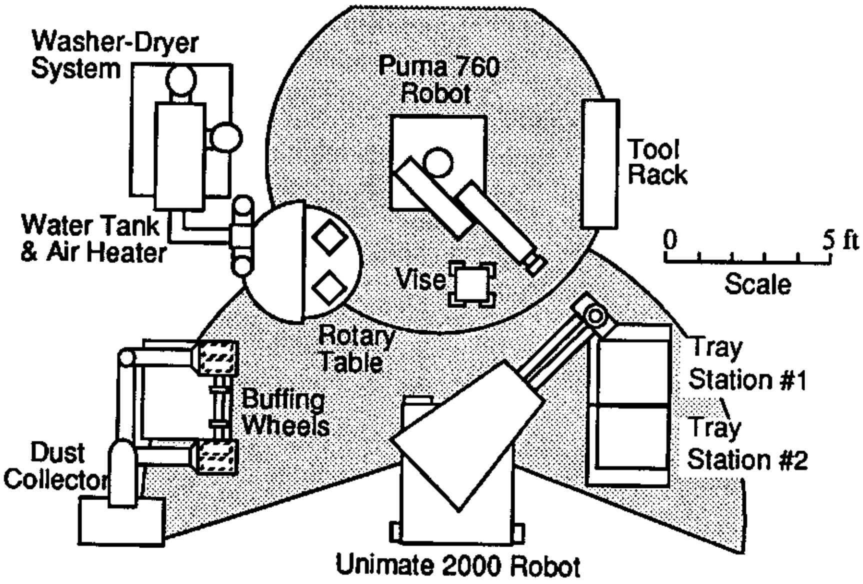


Figure 1 - The Cleaning and Deburring Workstation at the AMRF.

II. BASIC OLP IMPLEMENTATION

The lack of standard interfaces to and from OLP systems is a well known integration issue which exists in all components of Computer Integrated Manufacturing [6]. The flow of information from the CAD system, through the OLP system, down to the controller and back to the OLP system is interrupted by the lack of interfaces as illustrated in figure 2. The intent for the initial implementation was not to tackle an entire interface "barrier" but rather to chip away at it. Implementation of a basic OLP system focused on the problems of a CAD interface. The left hand barrier illustrates the need for a CAD interface to transfer accurate part design information to the OLP system.

Using the OLP system first involves transferring a CAD wireframe model of the part from a commercial CAD system (CADDS from ComputerVision) to a commercial OLP system (CimStation from Silma, Inc.) via the Initial Graphics Exchange Specification (IGES) [7]. IGES 3.0 is a standard file format for passing CAD data between systems. The imported IGES part model is added to the OLP world model. The operator then models the remaining workstation components within CimStation. Robot trajectories are created by defining frames on the graphics screen's rendering of the simulated workcell using a mouse and an on-screen pointer. The operator programs robots (for simulation) by the teach method or by entering absolute or relative tool coordinates and orientations. The user then generates programs textually and graphically to operate and synchronize all workstation devices such as robots, material handlers, fixtures and tooling. The resulting programs are tested and revised based on collision detection and other criteria. The final simulation is saved and the cartesian or joint space robot trajectories are post-processed for downloading to the VAL II robot controller. CimStation provides the simulation environment upon which we are developing additional modules such as environmental modeling. This seamless OLP implementation enables CAD and control information to travel quickly and reliably from design, through simulated testing iterations, to the robot controller.

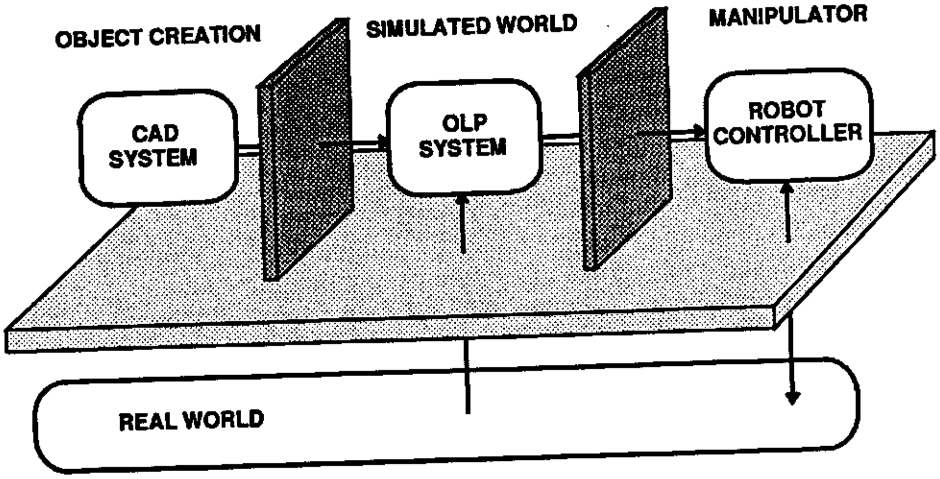


Figure 2 - Off-Line Programming Issues.

III. OLP ENHANCEMENTS TO THE WORLD MODEL

Integrating OLP to other systems such as CAD and robot controllers is both a necessity and a challenge. The major impediment to effective OLP, however, is the inconsistency between an OLP system's world model and the real world. The world model acts as an link to the real world for both the OLP system and control system [8]. The first part of the solution lies in improving the world model's geometric fidelity using calibration. The second part of the solution lies in having a world model that facilitates the off-line programming of sensors for execution by the control system. An adequate world model for generating robust off-line programs must include environmental models such as range (calibration), force, and vision. The first phase OLP implementation confirmed the importance of the world model and our work in implementing calibration and force simulation is illustrated in figure 3.

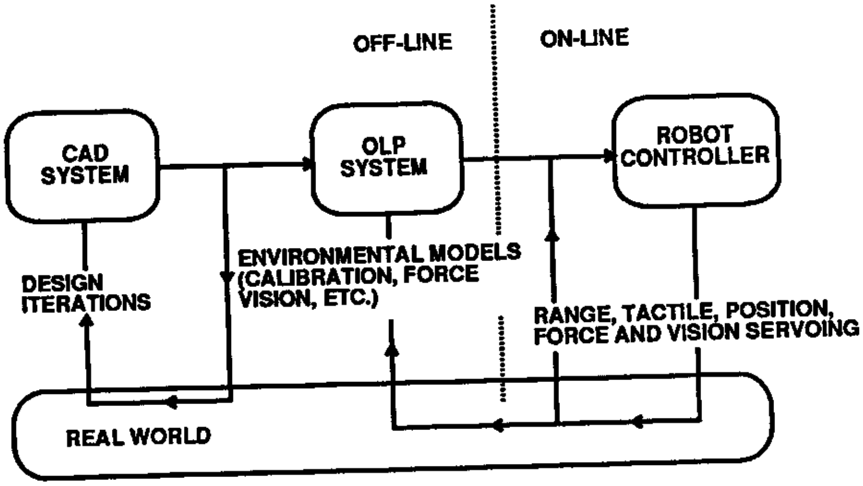


Figure 3 - OLP World Model Enhancements.

III.1 Environmental Modeling of Relative Positions - Calibration

The first step in improving the world model is to calibrate relative object positions based on measurements taken of the real world. An array of ranging sensors mounted on three normal surfaces of a fixed device is traditionally used to perform calibration[9]. Robot mounted non-contact calibration, however, is more flexible. This calibration method is made possible by compact ranging sensors such as ultrasound or recently developed laser triangulation sensors [10]. An instrumented gripper was built that consists of two ultrasound ranging sensors on each gripper finger. The ultrasound ranging sensors are aimed normal to a fixed hard surface and the delay of the return sound pulse is recorded and converted to a distance. The sensor control electronics are integrated with the CDWS controller enabling automatic data retrieval and manipulation [11]. The calibration gripper is equipped with a quick change adapter enabling the Unimate 2000 robot to attach or detach the calibration gripper when necessary. The instrumented gripper can perform part handling. In addition, the gripper manipulates a target when the object under calibration can not be used itself as an ultrasound measurement target. The RPS-300 Migatron ultrasound sensor's reliable range is between 3 and 14 inches and +/- 6 degrees off the normal. The accuracy of the sensor is specified to be 0.03 inches. Our implementation of the sensors resulted in a resolution and repeatability of 0.045 inche and 0.08 inche respectively. The Unimate 2000 robot, which performs the calibration, is repeatable to within +/-0.1 inche. Compared to the traditional fixed calibration device, our robot mounted ultrasound calibration scheme is non-contact, fast, flexible and automated. The configuration of our implementation, however, can measure only along two normal axis and around one axis. Measurement of the complete three dimensional position and orientation is achieved most effectively by mounting three ranging sensors in a triangle pattern, repeated on three normal surfaces such as that of a cube [12]. This configuration is also implemented easily as a non-contact robot mounted device.

World model calibration using ultrasound sensors consists of two steps; measuring the pose (location and orientation) of objects relative to the robot; and generating a three dimensional scalar map of robot end effector positioning errors in a volume surrounding a work area of interest. Both of these calibration procedures transform primarily joint space errors into cartesian space errors and are assumed valid for small distances and angles. Calibration results, therefore, are valid only in the vicinity of the calibrated object or volume. Measurements of object poses are uploaded to the OLP system for off-line calibration of object locations and robot trajectories, as illustrated in Figure 3. An error map, on the other hand, consists of several pose measurements within a volume of interest such as around a fixturing device. VAL II uses the error map on-line to compensate for positioning errors. Positioning errors for the Unimate 2000 in the vicinity of the CDWS vise, for example, vary between 10 and 20 percent.

Static calibration reduces the static errors of the world model only to within the limit of the calibration sensor's accuracy. Not only do calibration sensors have a finite accuracy, but also dynamic changes in geometry (for example due to temperature fluctuations or wear) are very difficult to model and/or track. On-line, real-time use of sensors is absolutely necessary to compensate for a dynamic environment. Reliable OLP programs, therefore, must include sensor programming.

III.2 Environmental Modeling of Forces

The baseline OLP system built on top of CimStation limits the user to position control of robots in a workstation. While helpful, position control alone is not sufficient for robust off-line programming of robots. The underlying assumption is that simulations will never be perfect geometric, kinematic or dynamic replicas of the real world. Due to robot positioning errors and world model inaccuracies, the real buffing wheel is not exactly where the OLP simulation represents it to be relative to the robot. Therefore, sensors must be used to compensate for errors in the workstation world model and inaccuracies associated with position control of robots[13]. Sensor programming of robot tasks uses sensor feedback from the environment, or environmental models, to account for these errors. An effective OLP system must be capable of generating sensor programs based on environmental models. The goal of environmental modeling is to map certain features in a subset volume of the workstation world model. Environmental models are developed using sensors such as proximity, vision and force/torque sensors. These environmental models are then incorporated into the OLP process to enhance the world model by providing detailed information about regions of interest within the world model. An example of environmental modeling is world model calibration via ultrasound proximity sensing introduced above. Development of a vision sensing model, to compensate for unknown part placement, is a future goal of this project. The following sections discuss work recently completed on environmental modeling of forces at the AMRF's Cleaning and Deburring Workstation.

Force/Position Model

The buffing of machined parts in our CDWS was chosen as the application on which to develop an environmental model[4]. The buffing application simply served as a vehicle for our research into environmental modeling. Robot errors in part placement into the rotating buffing wheel can result in inferior buffing or dangerously high forces on the part and the robot. The environmental model which was developed and implemented was a force/position(F/P) model of the buffing wheel. The F/P model relates buffing forces on a part to position of the part within the buffing wheel. The buffing forces were gathered experimentally using the force sampling end-effector shown in figure 4(a). The force sampling end-effector was designed and built at NIST specifically to obtain the relationship between buffing forces and relative position within the rotating buffing wheel. The force sampling end-effector is a box-like tool which contains a force/torque sensor. One of three different size probes, attached to the force sensor, peeks out through the faceplate. The probe tip is flush with the faceplate to avoid vertical (y axis) forces on the probe while the faceplate is large enough to look like an infinite plate to the spinning wheel. The force-sampling end-effector is also equipped with a quick-change adapter enabling the Unimate 2000 to attach/detach the end-effector when a new force/position model becomes necessary. Force readings were taken at 12.7 mm intervals both vertically (y axis) and horizontally (x axis), relative to the buffing wheel, and at 5 mm intervals into the buffing wheel (z axis). Surface plots generated at each y level of entry into the buffing wheel are illustrated in figure 4(b). These surface plots show the wave-like

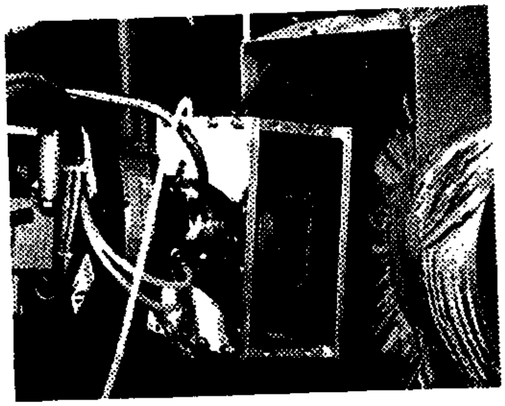
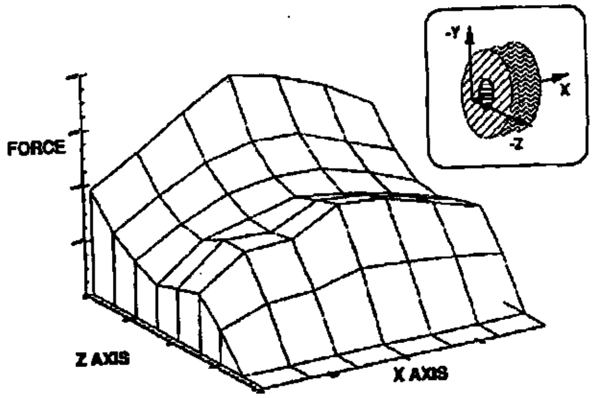


Figure 4(a)- Force sampling end-effector



(b)- Surface Plot of Forces (y=0)

representation of the forces incurred during buffing as the probe penetrates the wheel. The buffing wheel F/P model consists of a three dimensional compilation of these surface plots. Linear interpolation was used to determine forces at locations between the experimentally obtained nodes in the F/P model. The buffing wheel F/P model is applied off-line during simulation of the buffing trajectory to monitor the expected forces on the part. Given a part position within the buffing wheel, the force/position model outputs the expected force that the part will feel based on the experimental data of that buffing wheel. It should be noted that the force/position model is intended as an intermediate step toward on-line, real-time, sensor based robot programming to compensate for inherent world model inaccuracies and real world changes. Real-time force feedback, to a sensory interactive controller, would allow the robot to be programmed off-line according to the expected force/position model, and to actively look for that force on-line.

Force Display

The most visible feature of a graphical OLP system is the operator interface. The enhanced OLP system was built on top of the simulation capabilities of CimStation. Figure 5 shows CimStation's representation of the CDWS. With the simulation, the user can visually follow the movement of the robot as it executes its programmed trajectory. However, programs which make use of environmental models must report data from that model to the user. The environmental model gives the user more insight into how the robot interacts with its environment. In this case, the environment is the buffing wheel itself and the model represents the buffing forces acting on the part. The bar graph force display, as seen in the CDWS simulation, enables the user to adjust the programed buffing trajectory, off-line, according to the allowable forces of the task. The force/position model of the buffing wheel is applied during the robot's simulated buffing trajectory. The position of the part within the simulated buffing wheel is known and is monitored continuously using CimStation's object monitor feature. The part face is divided into smaller facets, in simulation, which are each tracked for collisions with the buffing wheel. CimStation senses a collision between any facet on the face of the part and the buffing wheel, and brightly colors the part and the wheel in simulation. The position of each facet within the simulated buffing wheel corresponds to a force within the buffing wheel's force/ position model. According to the F/P model, the expected forces on each facet colliding with the buffing wheel are

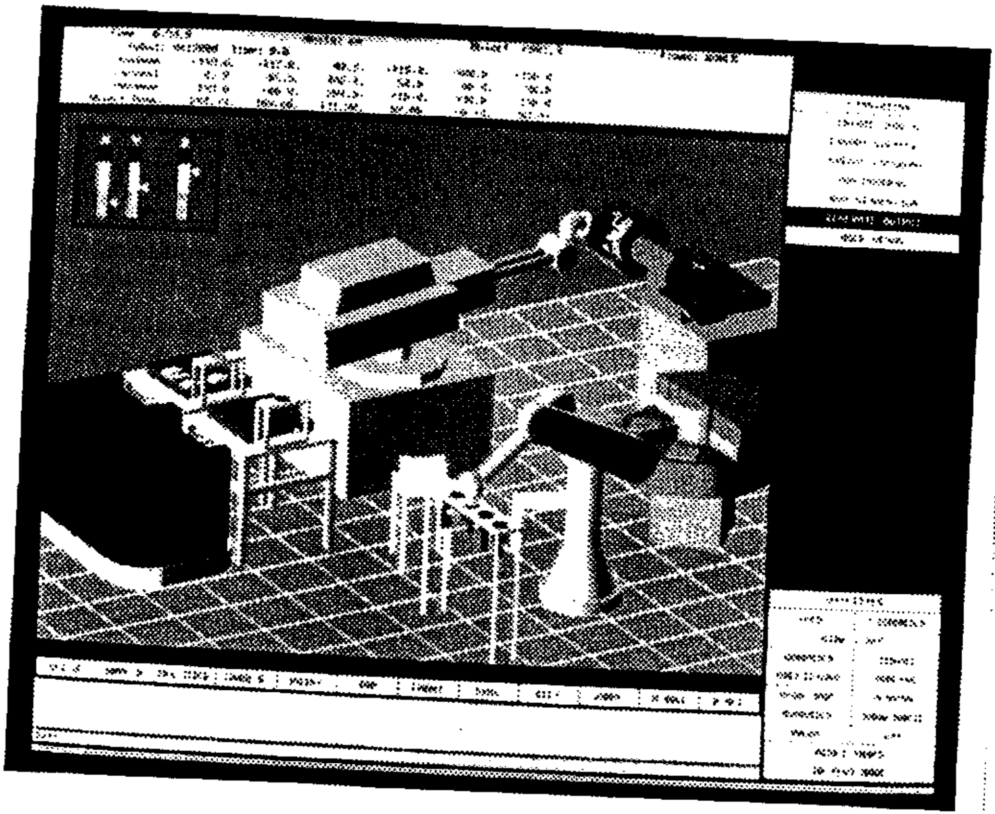


Figure 5 - CimStation Simulation of CDWS with Force Display

summed over the whole part. The total force on the part is represented in the simulated force display shown in figure 5. The expected forces in the x, y, and z directions are monitored using color coded scales. The color code is as follows: a green or yellow force is acceptable, a red force is unacceptable or dangerous. The expected forces on the part also can be monitored numerically in CimStation's message window. The force display graphically represents the force/position model and advises the user of excessive or inadequate forces incurred during a particular buffing trajectory. Therefore, the force display allows the user to visually examine the expected forces associated with a programmed trajectory and adjust the trajectory as necessary. By applying the force/position model off-line, we utilize environmental modeling to help develop robot programs and evaluate them for their safety and effectiveness.

Mosaic
Another trajectory evaluation tool, which we have developed for off-line use, is the mosaic pattern shown in figure 6. Each facet on the face of the simulated part is colored according to the length of time it is exposed to the buffing forces within the wheel. The mosaic pattern represents the time exposure of each facet over the entire buffing trajectory. The mosaic color code is similar to the force display. Facets which are red in color indicate excessive buffing time. Facets which are yellow and green indicate acceptable buffing time. Other colors indicate inferior buffing and white facets are untouched by the buffing wheel. Therefor, the mosaic pattern distinguishes the areas of most concentrated buffing for a given trajectory, allowing the user to adjust a particular trajectory according to the shape of the part or the desired buffing pattern. The user can develop programed trajectories which isolate sections of the part for safety reasons. For example, if the leading (top) edge of the actual part were to contact the rotating buffing wheel, excessive y forces would immediately slap the part from the gripper. This dangerous situation can be avoided using the mosaic pattern, off-line, to identify and change trajectories which include contact between the simulated part's leading edge and the buffing wheel. The mosaic pattern is a useful evaluation tool for analysis of off-line programmed buffing trajectories based on buffing time.

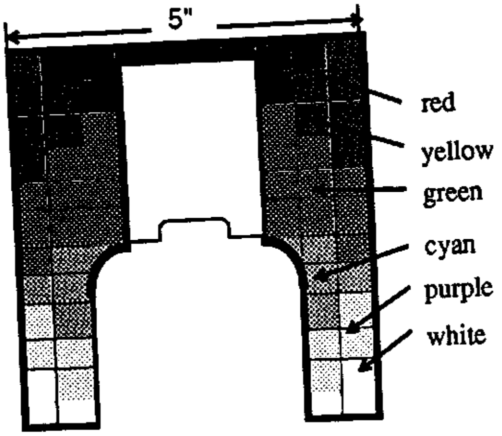


Figure 6 - Mosaic pattern on simulated part face.

IV. FUTURE OF OLP

Most OLP research consists of automatically generating robot trajectories and part handling sequences. In comparison, we at NIST are concerned with improving the effectiveness of currently available OLP technology. An OLP system can function as an effective man-machine interface to a sophisticated robot controller provided that the OLP system's world model is relatively accurate and flexible. Experience in implementing a basic OLP system has shown that environmental models of relative positions (calibration) and of sensory input are essential for generating robot programs off-line. Geometric calibration provides a basic level of world model accuracy in specific regions of interest. The flexibility needed to operate in a dynamic environment requires the use of sensors. Likewise, a robust OLP program must include sensor programs based on environmental models of position, force and vision. Environmental models of sensory input are used to generate flexible and robust programs off-line for execution by a sensory-interactive controller.

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Important Note:
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