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A GENERIC TELEROBOTICS ARCHITECTURE FOR C-5 INDUSTRIAL PROCESSES

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Abstract

The application of telerobotics to aircraft depot maintenance and remanufacturing is described and a telerobotics architecture for the application is discussed. Telerobotics will enhance process quality and could potentially decrease turn-around time and costs while moving human operators from hazardous work areas to safe and comfortable operator control stations. The approach is to augment, not replace, the human operator by blending human skills with robotics capabilities. Configurations of the architecture for telecrane, mobile carrier, and gantry applications are shown.

1. Introduction

This paper summarizes a study performed by the Jet Propulsion Laboratory for the Air Force Material Command (AFMC) Robotics and Automation Center of Excellence (RACE) to evaluate the feasibility of telerobotic solutions to C-5A heavy lifter aircraft maintenance processes and develop a telerobotics architecture for the application [1]. The architecture was developed for general depot maintenance and remanufacturing applications and applied to the C-5A application. Several implementation options suitable for insertion into a variety of depot applications that support the C-5A heavy airlifter are described.

The Aircraft Directorate at the San Antonio Air Logistics Center (SA-ALC) is responsible for depot level maintenance on the C-5 airframe. The efficiency and productivity of many of the required repair processes will benefit from the insertion of telerobotics technologies. Small batch size, feature uncertainty, and varying workloads make hard automation impractical for a wide range of depot processes. Systems are needed that can bridge the gap between manual control and complete automation. Supervised autonomy and shared control technologies provide intermediate solutions where the human and machine collaborate to perform tasks. In supervised autonomy, robotic tasks are interactively developed by the operator and then executed autonomously [2]. In shared control, control inputs during task execution are provided both by an operator, e.g., using a hand controller, and an autonomous system [3]. A more complete description of telerobotics systems can be found in [4]. The goal is to augment, not replace, the human operator by blending human skills with robotics capabilities.

Aircraft depot maintenance and remanufacturing provides a wide range of challenges for robotics. The physical scale of the applications includes stripping paint from a C-5 heavy lifter to remanufacturing small individual parts. The parts generally arrive individually or in small batches and a wide variety of parts are remanufactured. Due to the wide variety and scale of the applications, the maintenance and remanufacturing is now done almost exclusively manually. Example depot applications which the architecture must apply to include: painting of the C-5A exterior in a dedicated hanger facility; painting of removed piece parts in a robotic workcell; stripping of paint from the C-5A exterior in a dedicated hanger facility; surface finishing in form of removing material from patches and polishing metal to a high gloss finish in a robotic workcell; Surface cleaning of removed parts in a robotic workcell through application of bicarbonate of soda particulate stream; and sealing and desealing of aircraft fuel tanks.

It is expected that telerobotics can provide many benefits to aircraft depot maintenance and remanufacture. Limited manpower resources limit the number of aircraft that can be remanufactured. Telerobotics can augment the productivity of operators allowing a greater rate of aircraft throughput. In many instances telerobotics can provide better process control, e.g., paint can potentially be sprayed on an aircraft more uniformly than by an operator leading to reduced average thickness and cost savings in paint and aircraft weight. There are various hazardous work situations and environments in aircraft depot maintenance and remanufacturing areas including: chemical contaminants in the air and on shop surfaces; handling large, bulky support equipment; excessive vibration, especially of hand-operated equipment; and excessive atmospheric heat and humidity (up to 100 deg.F, 95% humidity). Telerobotics allows placing a manipulator in the hazardous environment and moving the operator to a safe and comfortable operator control station. Additionally, there are tedious applications which cause fatigue and subsequent errors, e.g., paint stripping and deriveting. Many of these tasks can be accomplished with the operator supervising a telerobotic system to perform the task resulting in greater efficiency and quality.

Since the telerobotic architecture was designed for use across a wide variety of depot aircraft and maintenance and remanufacturing applications, there are a large number of requirements it must satisfy. The architecture must accommodate different types of robotic manipulators with varying degrees of freedom with modular changes only to interface code. It must accommodate different types of transport and positioning devices for robots and piece parts with modular changes only to interface code. Initialization and monitoring must be automated and rapid. Human operations shall be able to safely operate within the range of motion of most manipulating and positioning devices through built-in safety protocols (hardware, software, and/or procedural) Smooth transitions to manual workaround modes must be possible during automation downtimes for maintenance, upgrades, etc. The architecture must accommodate different, unmodeled parts in all piece part applications. Software and hardware upgrades shall cause minimal down time.

2. Example Application: C-5A Aircraft Maintenance and Remanufacturing

The remanufacturing processes that support depot level maintenance of C-5 aircraft are representative of a wide variety of dual-use applications. Applications include stripping the external surface paint and then repainting, painting removed parts in a robotic workcell, skin repair, surface cleaning of removed parts through application of bicarbonate of soda particulate stream, surface finishing for patches, and polishing metal surfaces. A unique aspect of working on large airframes (the C-5A is over 247 ft. long and with a wingspan over 222 ft) is the requirement for large positioning systems. Several alternatives are possible. The first option is the telecrane concept where a special facility provides telecranes upon which the manipulators are mounted, as shown in figure 1. Such a telecrane facility is presently used at Kelly AFB which positions human operators around the aircraft for servicing applications (paint stripping with plastic beads). The telecranes do not have positioning sensors so either positioning sensors would have to be added, or some other method would have to be used to determine the position of a manipula-

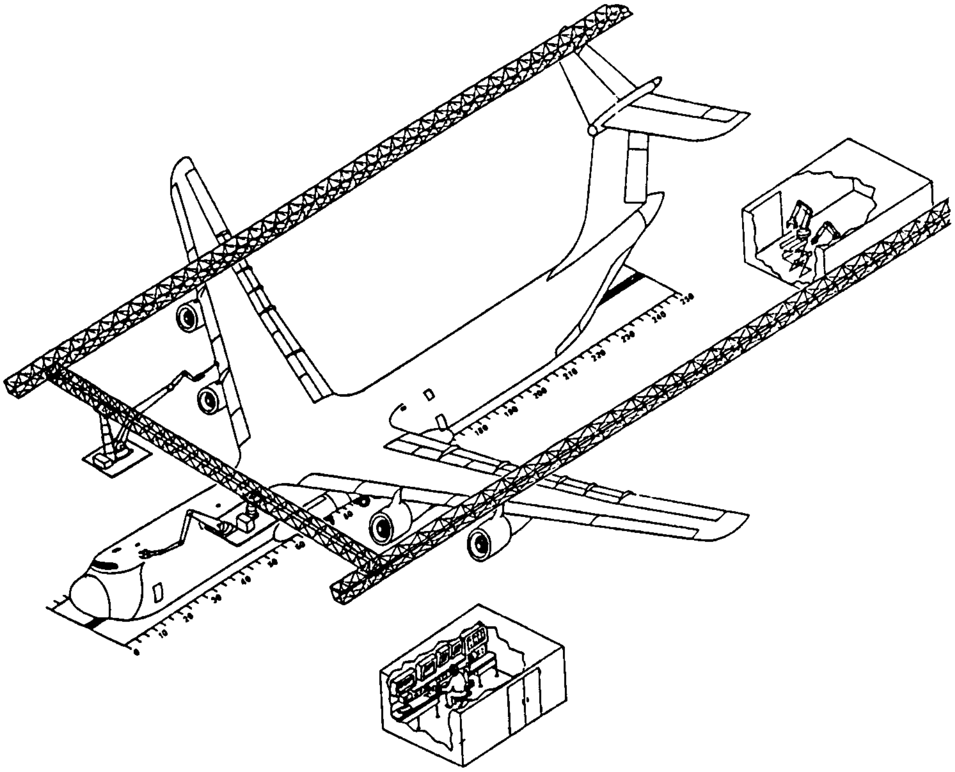

Figure 1: Telecrane concept

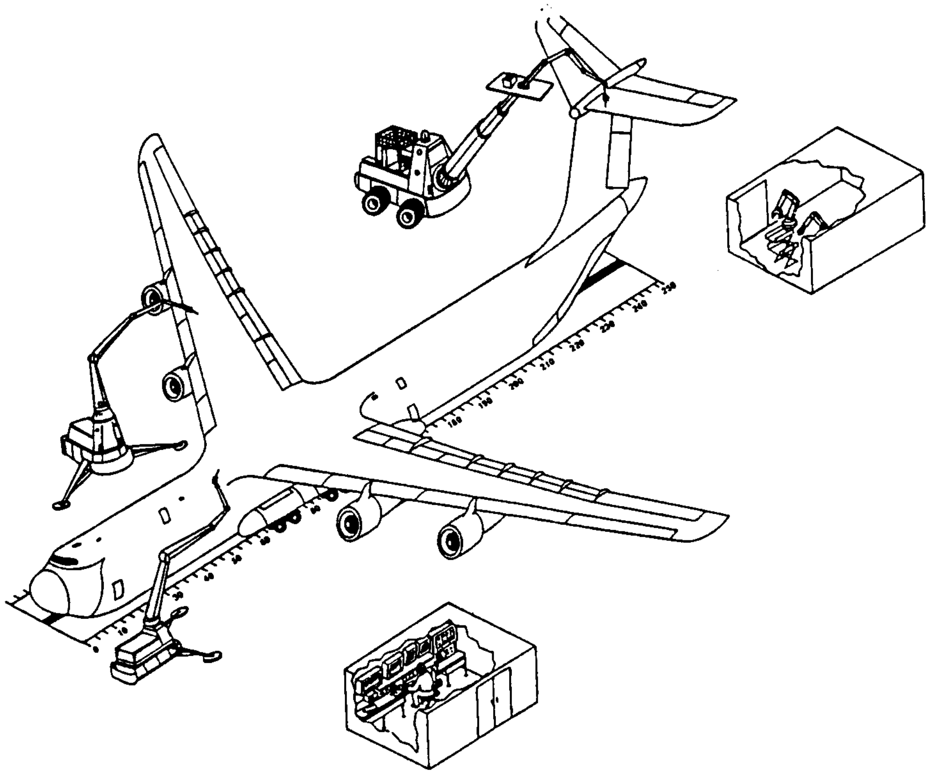

Figure 2: Mobile carrier concept

tor mounted on a telecrane. A second approach is to use mobile carriers where manipulators are mounted on mobile bases and the mobile bases are capable of being positioned around the aircraft, as shown in figure 2. Another option is to use an overhead gantry system where manipulators are mounted on mobile gantries. These transport methods apply to tasks which are done on the physical aircraft structure, such as painting, but there are also many tasks which are done on piece parts in separate workcell rooms such as repair and painting.

3. Telerobot Architecture

A telerobot architecture was developed to provide a near-term solution for implementation of a telerobotics system for C-5A servicing. Various architectures were evaluated such as the DOE GIST architecture[5], the NIST NASREM architecture[6], and the NASA/JPL local-remote architecture[2]. The architecture developed here has ideas common to all of these architectures. The GISC architecture provides the important concept of intelligent subsystems. The NASREM architecture provides valuable contributions in the coordination of task decomposition, modeling, and sensing. The NASA/JPL architecture provides the valuable concept of independent data-driven software modules to collectively provide general task execution capability.

The architecture developed for aircraft maintenance and remanufacturing is shown in figure 3. The architecture is nominally separated into local and remote sites corresponding to the location of the operator and robotic systems, respectively. The actual computing resources can be physically located near the operator, robotic system, or separate from either. The primary constraint is that sufficient communication bandwidth is provided. The basic concept of the near-term system is that there exist subsystems which have sufficient inherent capability to execute a wide range of task types either independently or in coordination with other subsystems. A task program is generated by the local site which describes the task to be executed either by an independent subsystem or through coordination of subsystems. The task program can be executed in various ways depending on the level of capability of the coordinating subsystems. The desired solution is to allow distributed autonomous control of the coordinating subsystems by separating the task program into subsystem task programs. The subsystem task programs can then be executed by a task program sequencer, possibly at the local site operator control station, or sent to the subsystem controller for execution within the subsystem controller, if possible. Subsystem inherent capabilities are programmed offline so that during task setup and execution the subsystems already have the necessary inherent task execution capabilities.

Various maintenance and remanufacturing scenarios provide a poorly structured environment so that sensing the environment is necessary to generate or update a model of the environment. For example, neither the manipulators nor the aircraft will be positioned accurately to a well known location a priori to task execution. Before, or during, task execution, the relative positions of the manipulator and aircraft area of interest must be determined. A main object knowledgebase is provided which stores global state information. Each subsystem also has its own database which includes relevant information from the object knowledgebase and information generated from sensing the environment during task execution. The object knowledgebase and subsystem database are kept consistent for common information. Environment modeling can be done in various ways. Autonomous subsystem tasks can include, or have primarily, modeling elements. Alternatively, the operator can interact with the system to aid in developing models of the environment. For applications which require highly accurate positioning, such as deriveting, it is likely that either sensor based position servoing or shared control will be necessary. An a priori generated model of the rivet pattern is unlikely to have the accuracy relative to the real rivet pattern that would be necessary for rivet removal. Sensor based position servoing would likely utilize real-time vision with an arm-

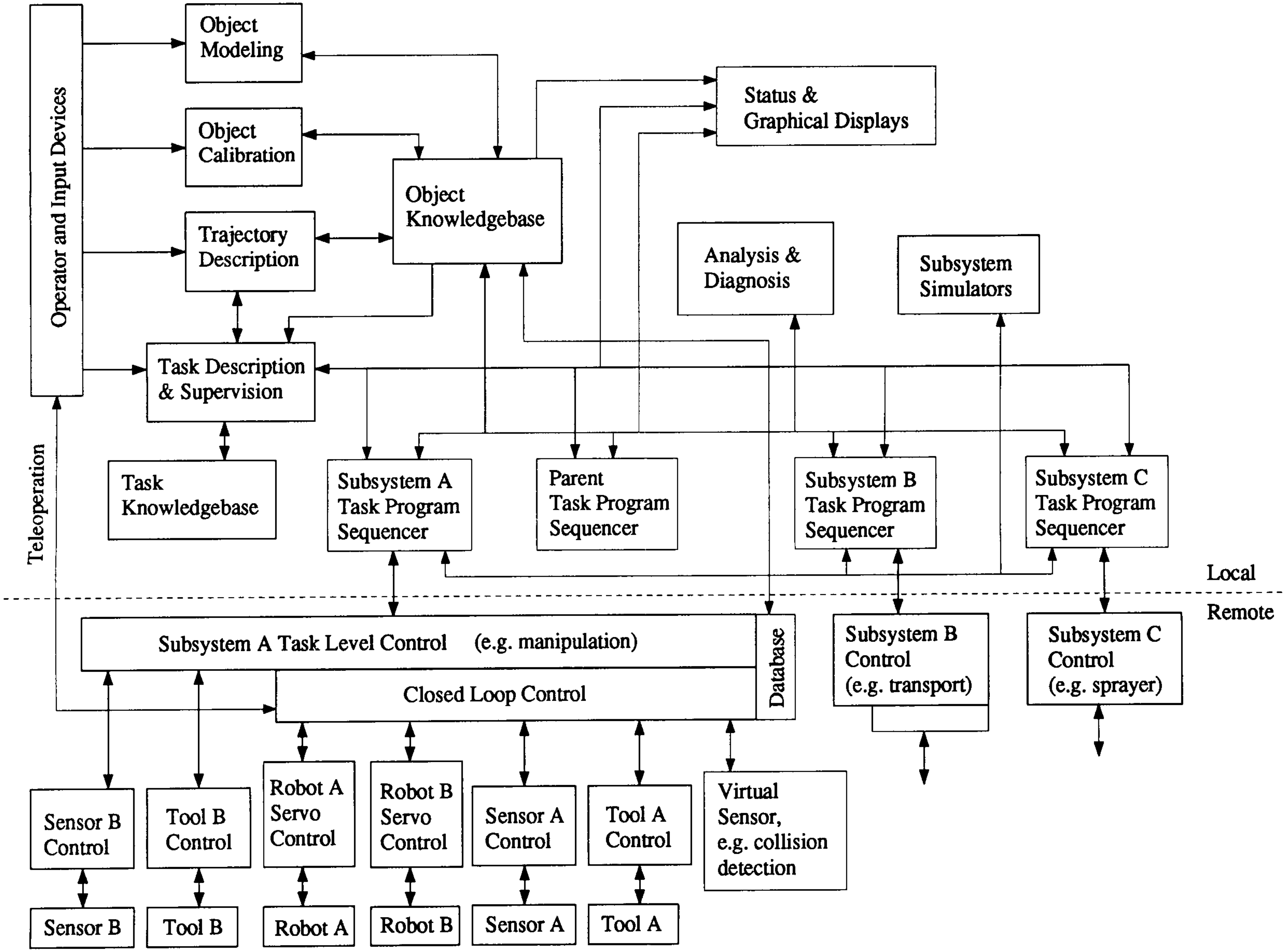

Figure 3: Telerobot architecture for aircraft maintenance and remanufacturing

mounted camera. A proximity sensor and possibly a sensor to measure surface tilt might also be used concurrently to control the position of the manipulator relative to the target. Rivets are difficult to find autonomously since the rivets have approximately the same color as the skin. Also, for previously repaired skin sections, the rivet pattern may not be known a priori. Therefore, for rivet removal, the operator can facilitate the use of the automated vision and sensing system by designating the rough location of the rivets to be removed. A video image of the skin section is provided on a monitor for the operator. If a model of the skin section is available, then it is overlayed on top of the video image (a ghosted image or perhaps wire frame). Otherwise an approximate model of the skin is generated to provide a three dimensional surface upon which to designate rivet locations. The operator then utilizes an input device to move a cursor to the rivet locations seen on the video image and selects the rivets to store their locations in the object knowledgebase. These approximate locations can then be used as starting locations for the automatic sensor based localization later. It is often useful in the task programs to specify objects and locations symbolically rather than with absolute locations. Then the task program can be generated independently of the actual locations. The actual locations of objects can be generated later either independently and stored in the object knowledgebase or as part of the task where operator input is automatically requested. Shared control can also be used to specify destinations. Here the operator uses an input device such as a six DOF hand controller to position the manipulator above the rivet. The proximity and/or tilt servoing could be occurring simultaneously to control the distance to the surface, depending on the method for removing the rivets. In this case the operator replaces the vision system.

It is desired that task description be as simple as possible for the operator. Therefore, as much intelligence as possible is designed and programmed into the system. For a sophisticated implementation, the operator would provide high level goal based information and the system would autonomously generate the associated task programs. A more realistic near-term system would require greater interaction with the operator to develop a new task. It is desired that the operator interact with the system primarily within the video/graphical environment, i.e., in a telepresence sense, both for task description and task execution. For task description, the operator would move the graphical manipulators via an input device such as a six DOF hand controller. The objects to interact with could be selected directly, or implied by proximity or context. The tool which the manipulator is carrying, along with the previous task steps and the selected object, provide a large amount of context information which the system could use to automatically suggest to the operator, or select, the next action to take[2]. The actions could be the subtask segments from the task knowledgebase.

The remote site subsystems will vary in the types of systems which they will control, in capability, and in vendor source. For some subsystems the task program will have to be translated into its command language. For other subsystems, a task program might be used directly. There are several types of control and coordination which may be needed within subsystem control and between subsystems. Closed loop control implies that there is a close coupling between sensory data and control commands to the devices. One subsystem provides cooperative control of its associated devices. Multiple subsystems can be coordinated to achieve a task goal.

Configurations of the architecture shown in figure 3 for telecrane, mobile carrier, and gantry applications are shown in figures 4- 6.

4. Evolution of the Telerobotic Architecture

The architecture shown in figure 3 supports near-term system development and evolutionary growth. Most of its basic features can be provided by existing vendors of automation and robotics technology. One drawback of current technology

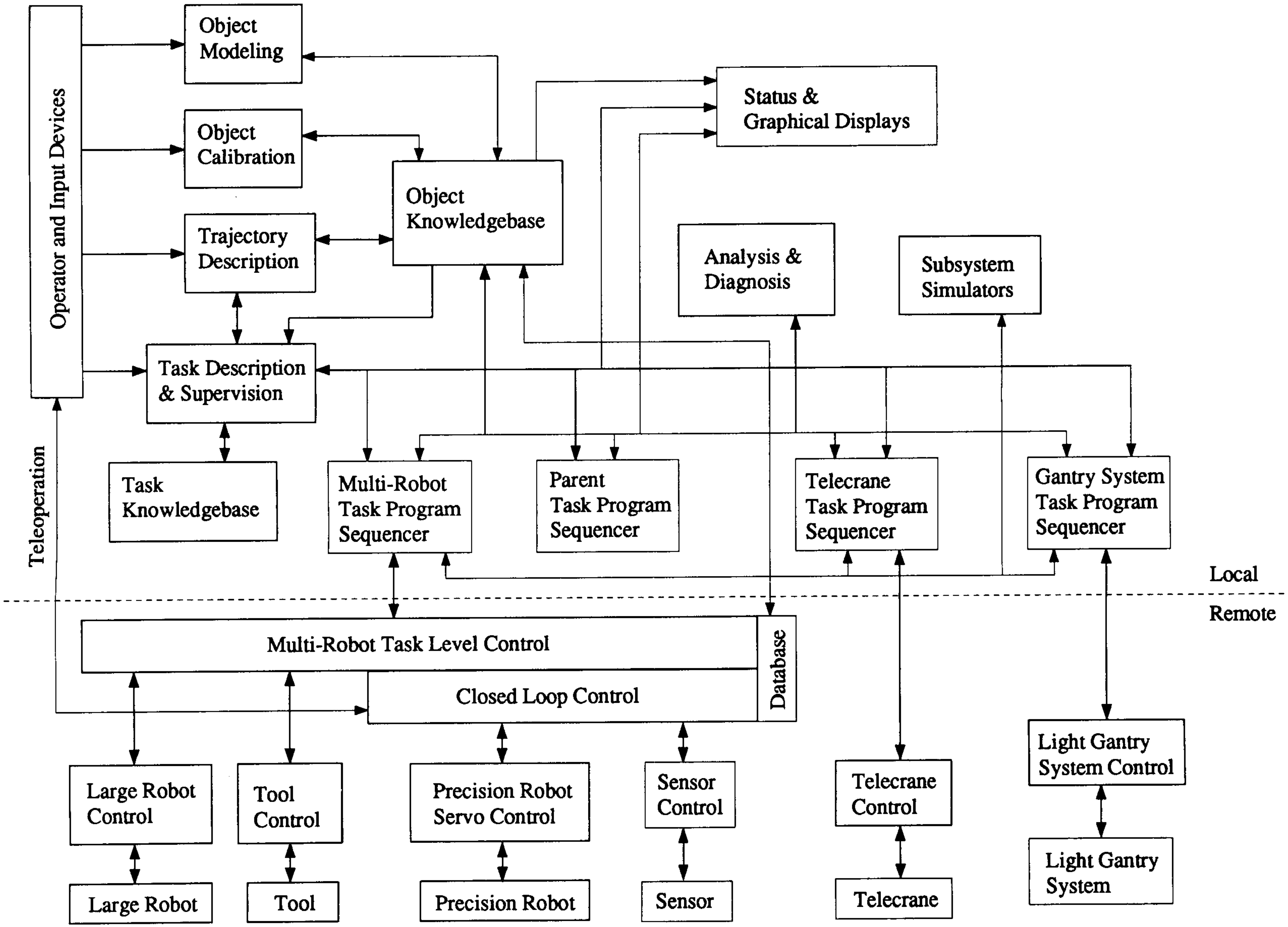

Figure 4: Focused Telecrane Control Architecture

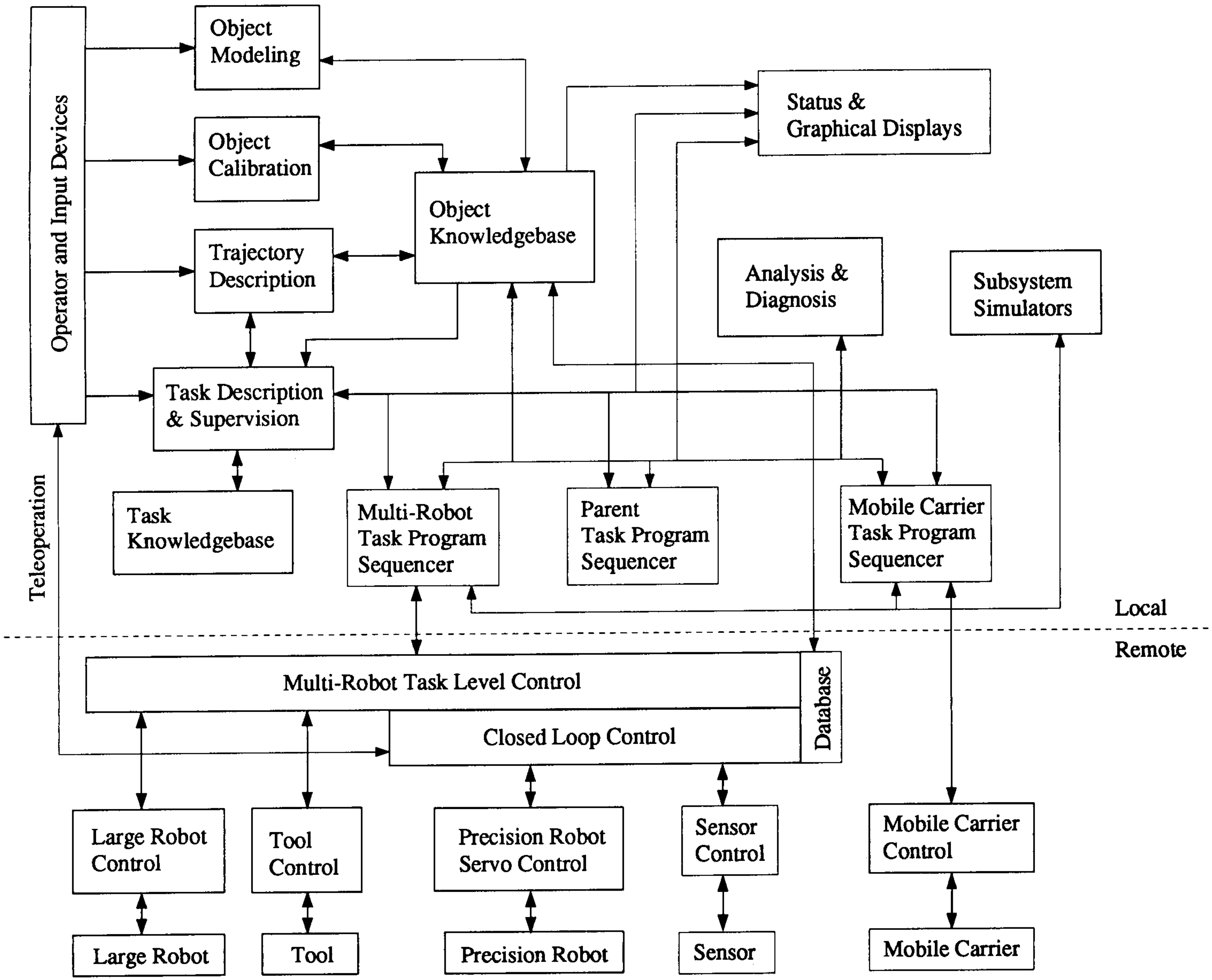

Figure 5: Focused Mobile Carrier Control Architecture

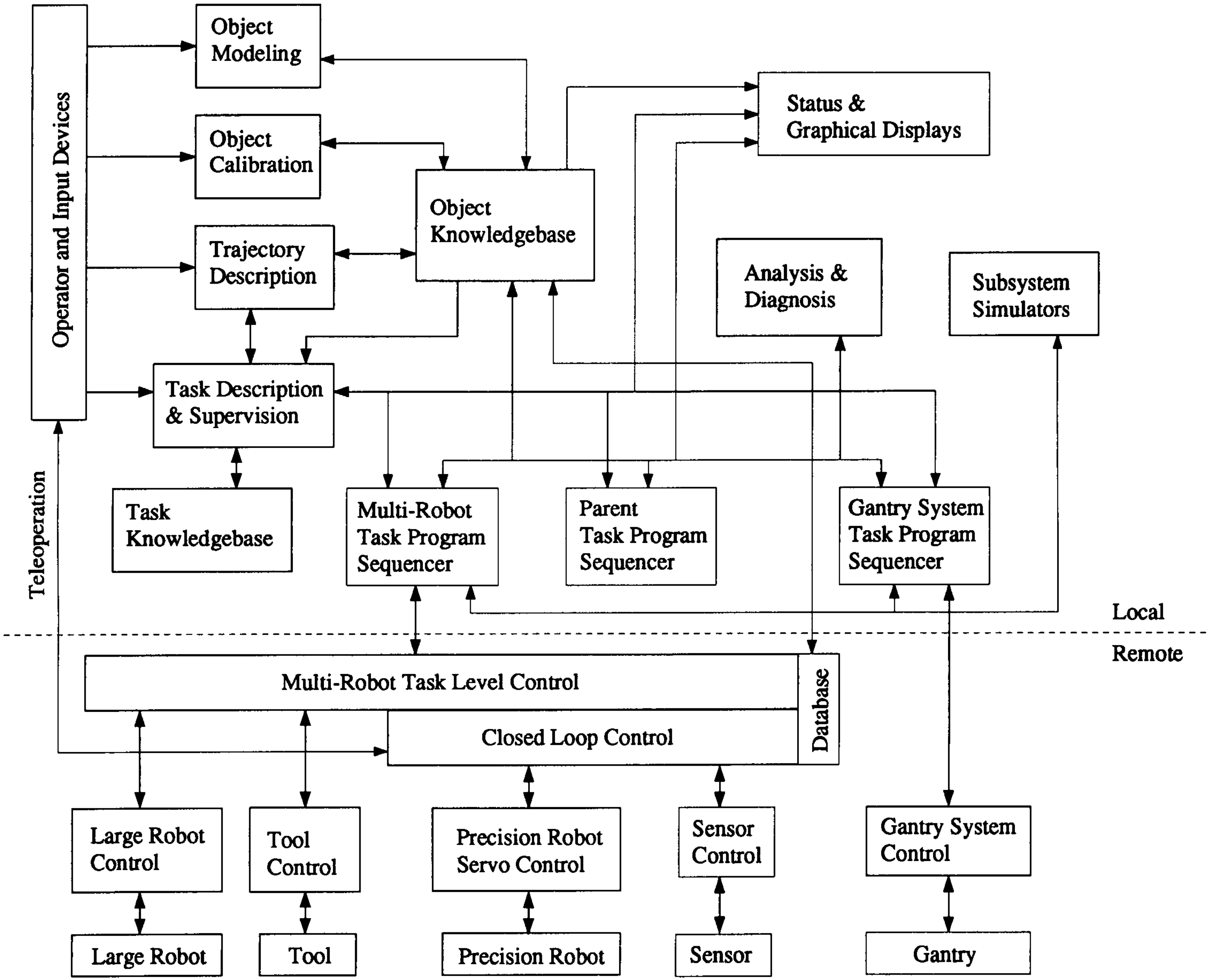

Figure 6: Focused Gantry Control Architecture

is that it is difficult to integrate systems from different vendors when a significant amount of control and modeling information is passed between layers in the architecture, since this information is often stored in different formats. The evolutionary direction of the architecture is to provide subsystems with increasing levels of intelligence which can be provided with goal based information rather than control based information which is prevalent with current technology. The intelligent subsystems would then autonomously request resources from other parts of the system such as the object knowledgebase. The resulting task programs would then be significantly smaller and quicker to generate. Protocols for communicating requests and information between the subsystems need to be developed. This approach is consistent with the goals of the Next Generation Controller program [7] which is developing a similar architecture for machine tool control. In the next year this effort will work more closely with the NGC effort to attempt to develop common interfaces and a common evolutionary architecture. The operator remains an integral part of the evolutionary intelligent architecture. In such an architecture the operator could become one subsystem with multiple capabilities or could be modeled as multiple subsystems. Also, the operator could act as one part of one of the subsystems such as the case described above where the operator performed the visual servoing for rivet localization. The system would then request input from the operator for information it cannot generate automatically, just as it would query one of the other parts of the system.

5. Conclusions

Application of telerobotics to aircraft depot maintenance and remanufacturing was discussed. The requirement to reduce technology insertion and system life cycle costs mandated the design of a generic architecture which can be implemented in the near-term and and still provide an evolutionary growth path. Most of the basic features of the near-term architecture are available from existing vendors. The evolutionary architecture utilizes increasing intelligence in the various modules of the system resulting in a more distributed autonomous control system. A commercialization study is underway.

Acknowledgements

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References

[1] Wayne Zimmerman. A generic telerobotics architecture for c-5 industrial processes. Technical Report (internal document), Jet Propulsion Laboratory, 1993.

[2] Paul G. Backes, John Beahan, and Bruce Bon. Interactive command building and sequencing for supervised autonomy. In *Proceedings IEEE International Conference on Robotics and Automation*, Atlanta, Georgia, May 1993.

[3] S. Hayati and S. T. Venkataraman. Design and implementation of a robot control system with traded and shared control capability. In *Proceedings IEEE International Conference on Robotics and Automation*, pages 1310–1315, 1989.

[4] Thomas Sheridan. *Telerobotics, Automation, and Human Supervisory Control.* M.I.T. Press, 1992.

[5] R. W. Harrigan. Intelligent system controller for remote systems. In *Proceedings International Symposium on Robotics and Manufacturing*, pages 741–747, Santa Fe, November 1992.

[6] R. Lumia. Space robotics: Automata in unstructured environments. In *Proceedings IEEE International Conference on Robotics and Automation*, pages 1467–1471, 1989.

[7] Bruce M. Anderson and Richard G. Holland. An open standard for industrial controllers. In *Proceedings International Symposium on Robotics and Manufacturing*, pages 953–960, Santa Fe, November 1992.