TECHNOLOGY INTEGRATION FOR A MOBILE, HIGH-PERFORMANCE ROBOTIC MANIPULATOR

Yee-yeen Chu, Ph.D.
Azad M. Madni, Ph.D.
Perceptronics
21122 Erwin Street
Woodland Hills, CA 91367
(818) 884-7572

ABSTRACT

This paper is directed to assessing component robotics technologies for a mobile high-performance dual manipulator. The manipulator system construct is defined in terms that allowed us to address the staged and modular integration best suited to integrated sensor and massively parallel processing capabilities. The technology development plan is then discussed. The issues related to pulling together evolving technologies currently being developed in the laboratories as well as other related efforts in the industry is also addressed. The main vehicle for purposeful integration of component robotics technologies is a detailed requirement analysis for a selected field robotic application. The complex and dexterous tasks required in coordinated mortar loading operations and maintenance functions are suggested in terms of the technological challenges posed in Superarm development. Finally, a graphics simulation and videotape of the Superarm concept demonstration is developed.

1. INTRODUCTION

A new generation of robotic systems are within sight that can perform highly complex tasks that usually have required human skills. These smart robots have the ability to see, touch, feel, and make movements accordingly; they can search, locate and grasp objects, and perform dextrous manual manipulations. They will be vastly more versatile than the early generation of simple "point-to-point" pre-programmed devices and direct position control devices. This is because of their ability to deal adaptively with work environments and to perform more refined tasks.

For example, a recent demonstration at the University of Utah laboratory (Biggers, et al., 1986) showed that a tendon-driven, four-finger hand can duplicate several performance characteristics associated with the human hand. At Stanford University and Massachusetts Institute of Technology (Fearing and Hollerbach, 1985), Lord Corporation (Lord Corp., 1985) and Case Western Reserve University (Rebman, 1985), robot fingers are being equipped with high-precision tactile sensors that produce images of manipulated objects just as human fingers can determine unfamiliar sizes, shapes, and orientation by physical touch. At Stanford University Aerospace Robotics Laboratory (Cannon and Binford, 1985; Cannon and Schmitz, 1986; Maple, 1985) sensor-based, flex-tolerate control schemes have been developed for the design of light-weight, high-speed manipulator arms. At Duke University (Wilson, 1985) a computer-controlled orthotropic tube is under development for potential light-weight, fast-acting arm structures. The fundamental changes in arm mechanism (Yang and Lai, 1985; Yang and Lee, 1984) have the potential for significant improvements in efficiency (i.e., workspace versus occupied space, payload capacity versus weight, work versus power ratios) and operation safety.

Supporting scientific work on methodologies for integrating mobile autonomous robotic systems (Raibert, 1984; Joshi and Desrochers, 1986; Madni, et al.,1982) has also produced various forms of hierarchical control software (Narasimhan, et al., 1986) and high-level command languages (Chu, et al., 1980). Advanced computation techniques and knowledge-based protocols for intelligent task automation (Honeywell, 1985; Martin Marietta, 1985) and autonomous vehicle control, employing distributed sensing, processing, and control, are also being developed (IEEE Council, 1986). Such protocols give high computational power to critical robotic subsystems that must function simultaneously (e.g., Salisburg, 1986).

In addition, many advanced manipulator subsystems developed or are currently under development. These include active visual sensors, laser range finders, acoustic imaging sensors, rare earth actuators, shape memory metal actuators; some are available as off-the-shelf components.

These component technologies are central to the Superarm concept development since the high performance is made possible only if individual components have suitable intrinsic behavior. The graceful behavior of musculoskeletal components in biological systems ideally serve as models for the design. In this respect, the use of off-the-shelf components in the critical Superarm elements may not necessarily meet the performance requirements from the viewpoint of overall system design. As such, each element of the system should be examined in a very general way to identify individual performance characteristics, as well as how the element will interact with other parts of the system.

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2. SUPERARM SYSTEM CONSTRUCT

Our field requirement studies (Chu, et al., 1986) have shown that the use of mobile, light weight, robotic devices have great potential for fulfilling field operation needs. These devices are potentially low cost and should continuously benefit from technology advances. They may be functionally distributed to allow incorporation into existing command, control and logistic networks. They can be instructed to perform various tactical and logistic operations. Several candidate scenarios were developed and explored within these operations. Each of the candidate scenarios were selected on the basis of the opportunity they provided for dexterous dual arm function demonstration with specific emphasis on situations where replacement of human capability was found to be highly desirable. From these scenarios the mortar loader and mortar crew finally were selected as the two most promising applications. The critical tasks for the Superarm as mortar loader and mortar crew were analyzed within a network-based task analysis model. These tasks were used as a basis for determining the integrated system performance requirements and desirable functional characteristics of component technologies that were deemed to be most suitable for near-term applications. The role as mortar loader and mortar crew is considered one of the most immediate payoff areas because it allows immediate use of many evolving technologies.

Figure 1 provides an overview of the functional attributes and technology required in the Superarm concept. The Superarm as configured here is an integrated, multi-processor controlled, dual-manipulator system that can move quickly and precisely, touch an object gently, grasp appropriately, adapt to the changing load, track and catch moving objects, and use two hand and arm cooperatively while constantly monitoring environmental conditions.

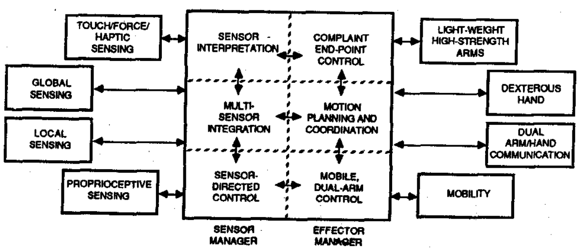

FIGURE 1 SYSTEM CONSTRUCT

As shown in Figure 1, the Superarm will consist of the following effector elements:

- Dexterous hand.
- Light-weight, high-strength arm.
- Dual, coordinated hand and arm system.
- Tracked moving base to provide mobility.

Colocated with the effector elements above are the sensing elements including:

- Touch, force, and haptic sensors.
- Global locating sensors.
- Local locating sensors.
- Proprioceptive or internal sensors

The locating sensors may consist of vision and ultrasonic sensors.

The functional requirements, available technology and technology gaps for each of these sersor have been assessed. These requirements were based on the analysis performed on the mortar loader and mortar crew task. These derivations were based on the elements of the task which determine the most difficult functions the arm must perform in terms of accuracy, speed, strength, dexterity, resolution, etc.

The compartmented effector and sensor system development will be integrated in a hierarchical task-oriented control architecture. The processing function is partitioned vertically into levels of command and communication. The basis control structure is a tree, configured such that each processing module has a single superior and one or more subordinate modules. The top modules, shown in the central portion of Figure 1, are where the highest level decisions and procedures are made and the longest information planning horizon exists. Plans and procedures generated at the higher level are transmitted on the next lower level of control as sequences of less complex but more frequent commands (Chu, et al., 1980). Thus, the higher levels deal with overall performance issues like action sequences, two arm trajectories, and sensor interpretation from different kinds of devices, including haptics and vision. The lower levels implement the message passing between concurrent feedback loops that control individual joint positions and stiffness.

The hierarchical nature of the system integration framework leads naturally to a top-down system specification and bottom-up system design, wherein choices of the central variables and measurements are made first. Various parallel sensing and control processing and feedback loops individually designed and developed can then be brought together and assembled into the overall, complex system. This hierarchical concurrent architecture thus allows the integration of various complex components to interact with each other by relatively simple communication schemes at various abstraction levels.

Data from each compartmented module will be exchanged using a message passing scheme. A dual arm control module may collect control information by sending selected data to another arm processor or may request an end-point control module to provide trajectory information. These tasks may run on any of the parallel processors, and the interacting tasks are allowed to communicate with each other as needed. Figure 2 shows a possible integration scheme for a hand-wrist-arm system with the hierarchical, task-oriented concurrent

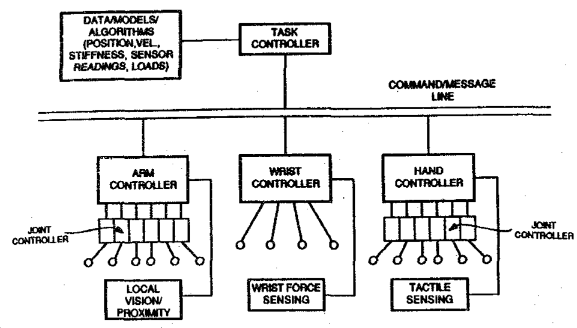

FIGURE 2 SCHEME FOR HAND-WRIST-ARM INTEGRATION

processing architecture. The communication line may consist of parallel or serial lines and provide: exchange media for messages and commands from the task controller; responses from the arm, wrist, and hand; and data transfers between the controllers and the task algorithms data base.

3. RESEARCH AND DEVELOPMENT PLAN

To meet the challenge of critical manipulation tasks in an unstructured, uncertain and hazardous field operations, a multi-year R&D plan is formulated for the development of the Superarm system. The overall goal of the plan is to create a new generation of "high performance manipulator technology" by seizing an opportunity to leverage recent advances in mechanical hands, compliant arms, sensor and control system development.

In contrast with previous manipulator systems, the new generation manipulators will exhibit approximate anthropormorphic capabilities for handling and manipulation. The manipulators will also have capabilities that accommodate the task environment through a sensor-based compliant control, and the user requests and instructions through a high-level command language.

This section describes the plan and methods for orchestrated interaction between selected field applications and the evolving technology base. Figure 3 presents the overview of the program goal to demonstrate the Superarm as a mortar crew. Table 1 presents an overview of the key advances for program demonstration. The goal achievements will be showcased in a stage development and demonstration which, when completed, will generate the following products:

- Technology demonstrations with operational field applications.
- Specifications or standards for next-generation robotic manipulators.
- Well-defined thrust of strategic robotic technology.
- Working prototype ready for transition to field use.

To achieve the program goals, we suggest establishing an explicit set of modular system function capabilities. Each one, such as a sensor-based dexterous hand, requires the generation of a "technical committee" that is responsible for evolving that technology.

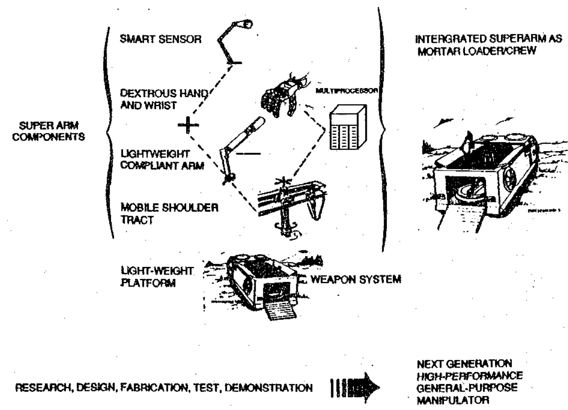

FIGURE 3 A MORTAR CREW DEMONSTRATION

. HIGH-PERFORMANCE, LIGHT-WEIGHT, EFFICIENT DRIVE SYSTEMS.
. EFFICIENT DYNAMIC AND CONTROL ALGORITHMS AT HIGH SPEED COMPUTATION.
. LIGHT-WEIGHT COMPLIANT MECHANISMS AND CONTROL.
. HIGH STRENGTH, DEXTEROUS END EFFECTOR.
. ADVANCES IN MULTIPLE SENSOR FABRICATION, INTERPRETATION, AND INTEGRATION.
. ROBOTIC COMPONENT FABRICATION AND SYSTEM INTEGRATION TECHNOLOGY.
. NEW THEORETICAL INSIGHTS IN DYNAMICS, CONTROL, AND MECHANICAL DESIGN OF ARTICULATED MECHANISMS.

TABLE 1 CRITICAL MANIPULATION REQUIREMENTS

In addition, we suggest initiating efforts in two areas of technology integration at the beginning: a dexterous hand and a compliant arm. Each of these areas will start on several fronts, including mechanical design, compliant end-point control, actuator drive, grasp manipulation algorithms and sensory integration. Details of these areas are described in Figure 4.

Certain component technology research should be conducted in parallel with the "pilot-studies" early on to position the technology for filling in the technology gaps later. These pilot studies may include: haptic sensor, micro-actuator, compliant structure, and dual, light-weight arms. In addition, certain component fabrication should be developed in pilot-line from early on to support the later development requirements. These include rare-earth actuators, system modeling and simulation, prototype brassboard, and an operator-system interface.

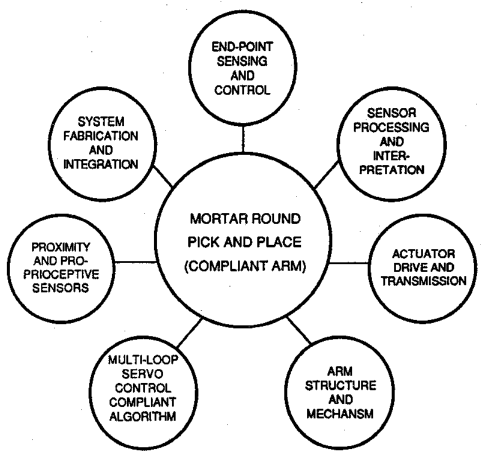

FIGURE 4 REQUIRED TECHNOLOGY DEVELOPMENT

Therefore, we suggested conducting the technology development via compartmented functional modules integration. Each of the functional modules are described in Table 2.

COMPONENT TECHNOLOGY	INPUT	HORIZON	RISK
1. HAND (Sensor-based) - Alternative Mechanical Design - Drive (Power, Regulation and Routing) - Data Processing - Control - Sensor - Local Integration	• UTAH/MIT • STANFORD/JPL • SALISBURY • OTHER	Partially Integrated in 2 Yrs	High Risk On Hardware
2. ARM (Integratable) - Compliance - DOF Configuration - Drive Distribution - Payload/Structure Ratio - Platform/Base Dynamics Integration - Control - Internal Sensing, Performance, Flexing, Computation Requirements - Coordination with Hand	• STANFORD • CMU • MIT • JPL • ONRL • UCLA	Initial Compliant Arm With Position-Force FB Control In 2 Yrs	Medium To High Risk on Hardware and Software
3. DUAL ARM Hand - Work Space Dynamics - System Coordination (Geometry, Dynamics, Including Hands) - Algorithm and Sensing requirements - Flexing, Compliance - Collision Aviodance	• STANFORD • JPL • WASHINGTON • UCLA	Dual- Arm Without Hand In 2-3 Yrs	Medium To High Risk On SW
4. VISION AND NON-CONTRACT SENSING - Special Local Vision Plus Global Vision - Proximity Sensing	• STANFORD • UPENN • CMU, MIT • HONEYWELL	Local Vision With Hand In 2 Yrs	Medium Risk On Miniturization and Scoping
5. MOBILITY - Stability and Compliance Control - Guidance and Avoidance	• ALV PROGRAM • STANFORD • CMU	Simple Guidance/ Avoidance Implementation In 2 Yrs	Medium - High
6. OPERATOR INTERFACE - Control and Display - High Level Command	• JPL • MIT • PERCEPTRONICS	Prototype Control Station As Needed in 2 Yrs	Low - Medium
7. SYSTEM AND MODEL SIMULATION AT MACROLEVEL - Major Subsystem - Integration Environment	• NONE	2 Yr Simple Runnable Model	Low
8. PROTOTYPE BRASSBOARD PROCESSOR - HW andSW Architecture	• STANFORD	2 Yr Simple Parallel Configuration	Medium

TABLE 2 COMPONENT TECHNOLOGY DEVELOPMENT

4. RECOMMENDATIONS AND CONCLUSIONS

In this study, we have provided a formal analysis and a development framework for integrating component robotic technologies into a Superarm capable of satisfying operational requirements associated with a high-payoff field scenario.

Current robotics technology base was evaluated in terms of both promises and limitations of component technologies in relation to the proposed application and demonstration scenarios. As a result of matching technological capabilities against scenario task requirements, recommendations were made in terms of which research products would have a high likelihood of being successfully introduced into an integrated system demonstration without "force-fitting." In addition, a suitable system integration framework was developed along with the appropriate development strategies. The "compartmented" integration framework and the proposed component technology mix are summarized in Figure 5.

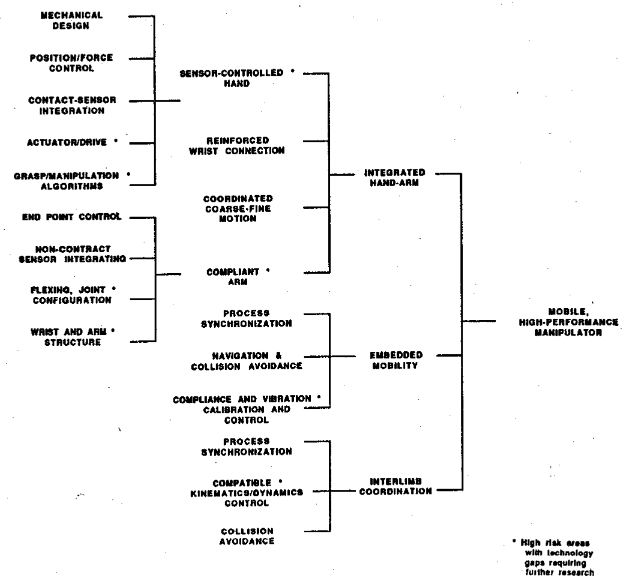

FIGURE 5 TECHNOLOGY INTEGRATION

Based on the above framework, it appears that while there are a number of off-the-shelf robotic components available, many of them are not suitable for integration into the Superarm. The components that need further development include those falling in the critical performance path, such as hand actuators, arm actuators, transmission systems, arm structure, compliant hand control algorithms and kinesthetic and cutaneous tactile sensors. Most of these items, although readily available, reflect their origins in fixed automation. Consequently, their performance tends to be constrained not by technological viability but by economic or availability factors. As a result, these off-the-shelf components that have limited the abilities of manipulators today cannot serve as the basis for the high-performance robotic arm we plan to develop. Therefore, we suggest that these technology void areas be supported so that the researchers produce reliable, high-quality prototypes that can be inserted in the integration program in a timely fashion. It has been argued that high performance systems are possible only if individual components have suitable intrinsic performance characteristics.

On the other hand, there are other sets of component technologies for which off-the-shelf items are mature enough for the proposed applications so that further research simply will not impact the desired performance dimensions of the overall system. These technologies include general-purpose vision components, high-level control and planning algorithms, and certain types of parallel processor computers. These off-the-shelf component items can provide cost and time savings while playing prominent support roles in the overall system integration. Our rationale here is that we are not trying to break new ground in peripheral manipulator technologies but rather demonstrate the feasibility of "performance multiplication" with the integration of intrinsically compatible component technologies.

In so far as rapid prototyping of the Superarm system is concerned, while an evolutionary integration approach is strongly suggested, there is no well-conceived, pre-established integration framework that encompasses all of the requirements of the Superarm. Nevertheless, a hierarchical, task-oriented, multi-processing command structure presented in the body of this paper is the framework of choice for the "compartmented" integration of component technologies identified within the Superarm construct. A real-time mediator program is suggested for determining which component subsystem to communicate with given the prevailing situation and subsystem requests without jeopardizing the integrity and execution of the overall processing and control algorithms.

Finally, we have developed an implementable "technology pull" plan that is underscored by two key themes: the careful fostering of selected robotic component technologies and the orchestration of timely technical interactions with challenging field applications. The application scenarios provide the vehicle and testbed for demonstrating the feasibility and subsequent refinement of new generation manipulation capabilities that achieve near-anthropomorphic performance. We strongly recommend that complete mechanized task components be analyzed and a well-defined integration framework and interface be specified prior to the overall integration and full-scale implementation of the Superarm system.

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