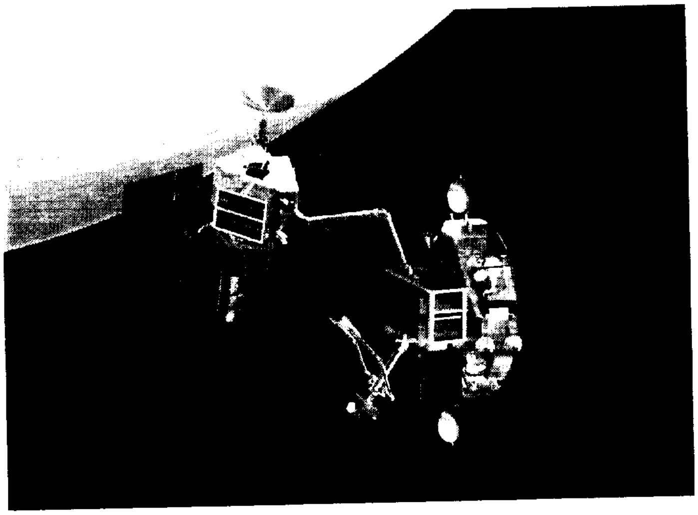
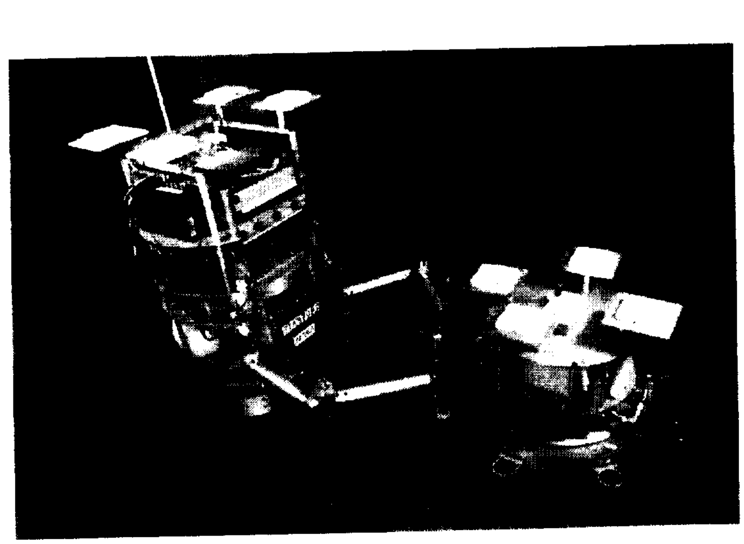


FINAL REPORT
on RESEARCH for the NASA on

CONTROL OF FREE-FLYING SPACE ROBOT MANIPULATOR SYSTEMS



FINAL REPORT
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Submitted to

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By

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Research Performed Under NASA Contract NCC 2-333
For the period November 1984 through April 2000

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FINAL REPORT
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INTRODUCTION

This is the final report on the Stanford University portion of a major NASA program in telerobotics called the TRIWG Program, led strongly from NASA Headquarters by David Lavery

This portion of the TRIWG research was carried out in Stanford's Aerospace Robotics Laboratory (ARL) to (1) contribute in unique and valuable ways to new fundamental capability for NASA in its space missions (the total contribution came from some 100 PhD-student *years* of research), and (2) to provide a steady stream of very capable PhD graduates to the American space enterprise.

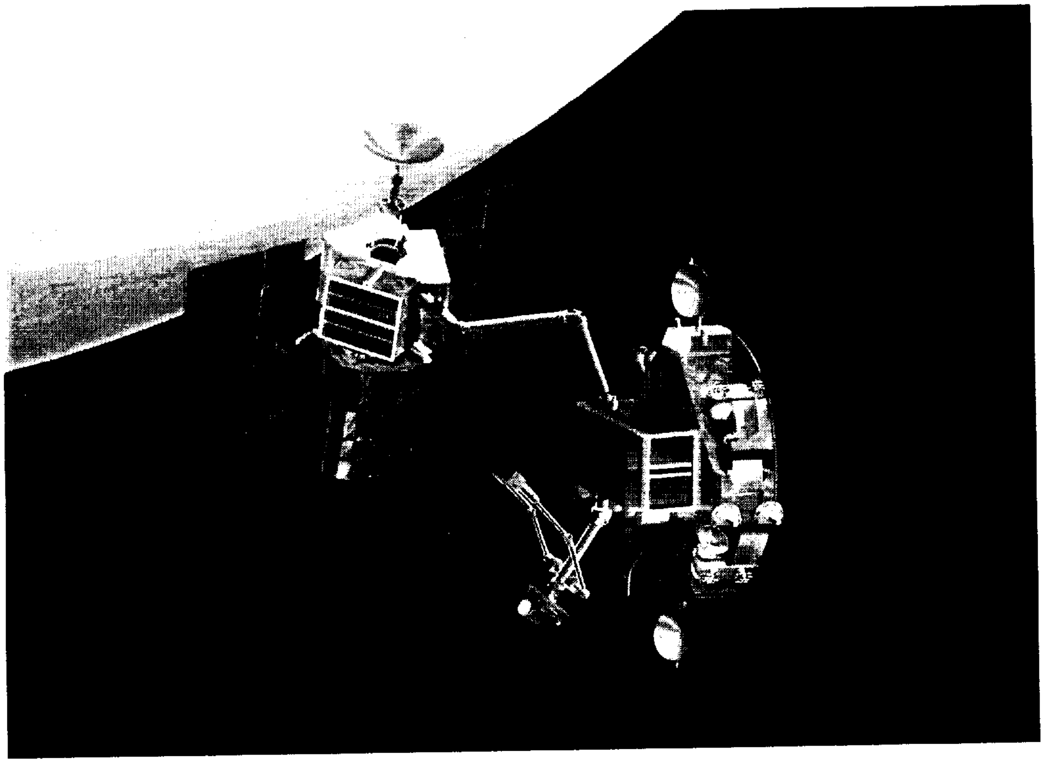
ARL graduates to date -- and NASA's Central Role
By year 2000's end, ARL will have graduated 46 PhDs (the final 7 have passed their thesis defense and will finish its writing in the next few months). Every one has contributed new basic concepts, and has fully demonstrated those concepts in experiments that had never been done before. These PhD graduates are listed in Table I, with their individual area of research contribution. Students supported directly by NASA TRIWG funding are indicated by "N." In Part II hereof is each thesis abstract.

The valuable roles in the national arena where the subsequent professions of these graduates have taken them are also shown in Table I. They are making a difference.

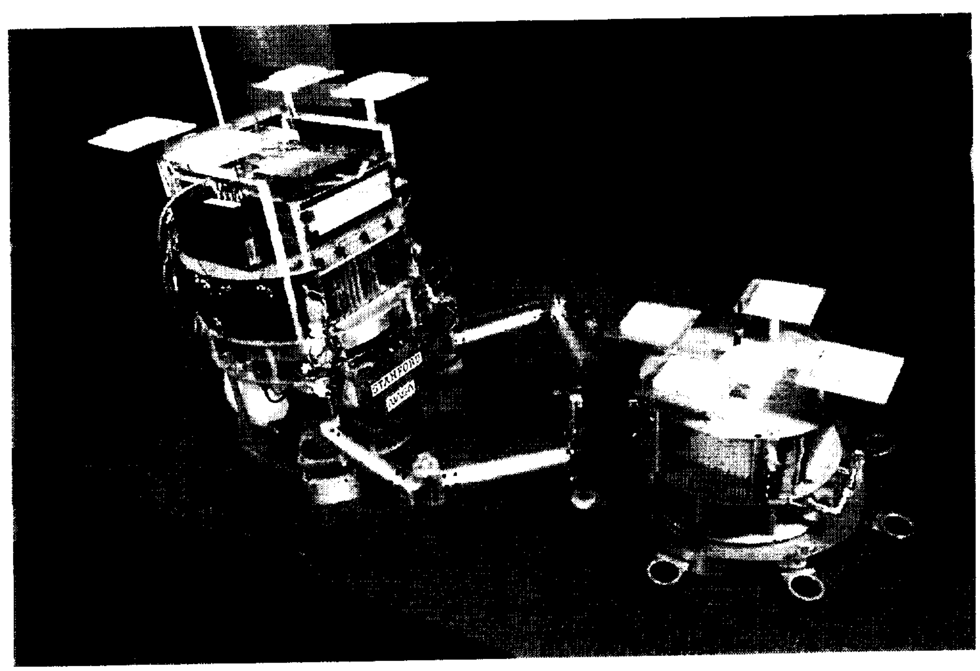
Over the period of this grant, NASA has provided about one-half the total support for ARL's team, and for much of its capital equipment. The grant has supported all or a substantial part of the research of 23 of the 46 PhDs achieved by ARL's students to date (and has also supported the initial year of 4 more candidates who are now well under way under new NASA or other funding). For part of their time, 4 of the 23 graduates have also had fellowships from NASA centers, 12 from NSF or DOD, and 5 from other sources; but NASA TRIWG funding was sustaining for all 23 students noted N; and NASA funding began only after each one's MS degree was completed.

Throughout each year of this grant there has been a diverse team of about 18 PhD students working with either two or three professors, and supported by one electrical and one mechanical design engineer plus the laboratory's resource manager. These highly interactive students have drawn strongly on each other to pursue, always experimentally, the focused mission of ARL -- with the research for NASA TRIWG at its core.

Figure 1. Free-Flying Spacecraft, and their quite-faithful (2D) emulation in ARL.



a. A free-flying space robot (FFR) tending a space vehicle.



b. A two-arm, zero-g/zero-drag FFR on ARL's granite table, capturing another spacecraft. (Note GPS antennas on both FFR and target spacecraft.)

ARL's Focus on NASA's Missions

ARL's focus is on the human/free-robot team, a seamless total system, with the human at the task-strategy and task-command level, and the semi-autonomous free-flying robot -- nearby or distant in space, *FIGURE 1* -- planning its own assigned *whole tasks* under way in real time as it carries them out quickly and with precision. What we've achieved is a total leap beyond the conventional, primitive "teleoperation" process that has gone before, wherein the human must personally send detailed commands to the robot's joints and propulsion components.

Instead, ARL's new systems enable a human to give *Task-Level* instructions, not about the robot's movement, but about the moves a physical object is to be caused to make in an unstructured environment: "That satellite is to be captured -- gently." "That free-in-space beam is to be connected into that truss at that point." "The nose camera on that free flyer is to be replaced with this new one." By controlling from the task level, the human is free to focus on strategy -- and on the unexpected -- while the robot plans under way and carries out the full sequence of whole tasks the human has commanded *re the object* : a powerful combination, and a challenging one. The new core technology is **Object-Based Task-Level Control (OBTLC).**

Each PhD candidate in ARL conceives and builds a new total system for carrying out a new kind of object-motion mission. And they draw strongly on each other.

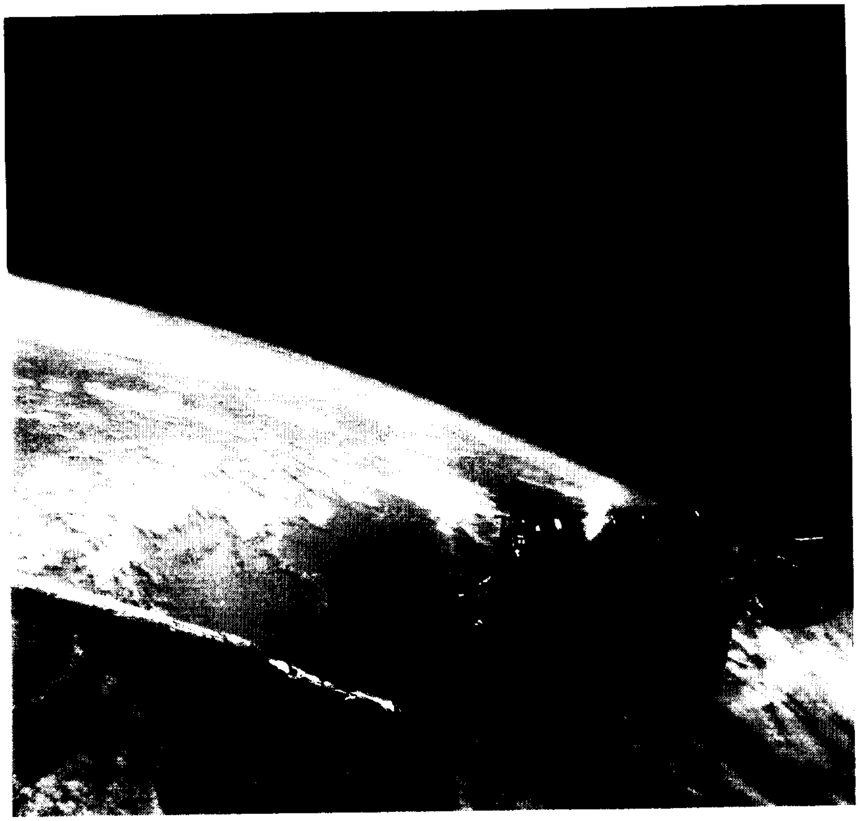
By way of preview, here are some *Highlights* of things PhD student teams in ARL accomplished -- each one carried through to full experimental proof of concept. The bold letters -- **a, b** -- refer to the Sections of this report that describe each project:

First-ever stable *end-point* control of a very flexible arm, **g**.

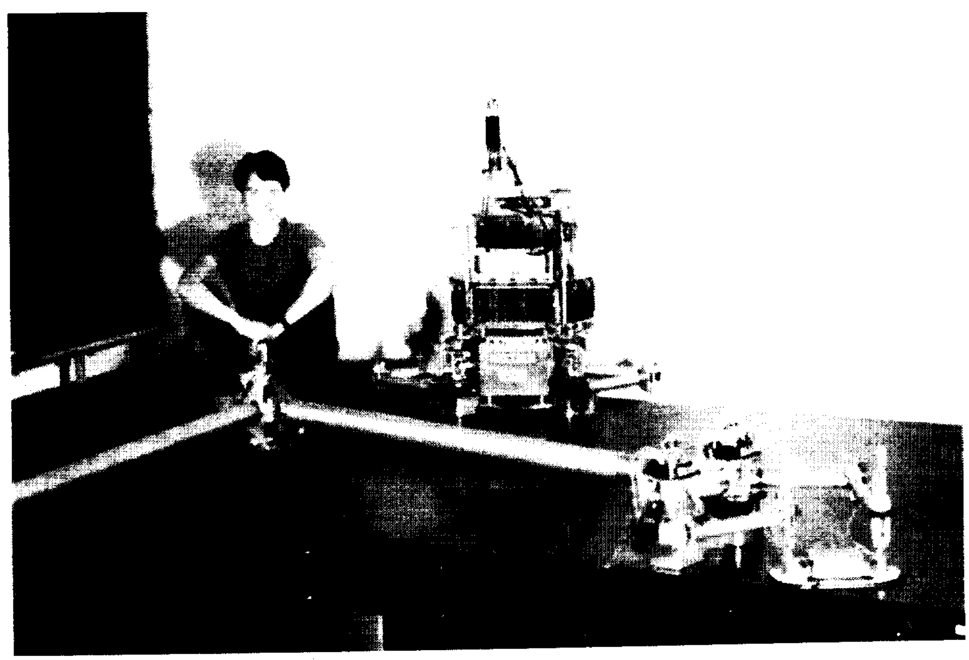
Invention of OBTLC architecture, **a**, which takes the human to a very high level in every one of the following human/robot systems, all shown experimentally:

- Free-flying space robots with Autonomous Real Time Planning, **b**, Fig. 7.
- Free fliers with neural-network control, **j**.
- Very Flexible RMS with quick, deft two-arm Surrogate Human at tip, **h**, to capture and manipulate free-flying spacecraft, Fig. 2.
- Autonomous *self-planning* assembly: Network Data Delivery System, **a**.
- GPS(only!) control in 3D: Wins national helicopter contest, **c**, Fig. 8;
- First *indoor* GPS system, **d**, controls 2D space vehicles, Fig. 1b.
- Interferometric Astronomy model: self-calibrating GPS (to 1 cm), **d**, Fig. 9.
- Mars Rover, deploying self-calibrating GPS system (few cm accuracy), **e**.
- Autonomous robots under water that fetch and deliver objects, **i**.
- Autonomous underwater sea-bottom mosaicing and station keeping, **i**.
- Adaptive Control Advances made deeply in every experimental venue, **j**.
- Architecture for new Cape Kennedy launch processing system (by RTI).

Air-cushion-supported two-cooperating-arm free-flying robots perform (in 2D) exactly as they would in space, *FIGURE 1b;* and with that test venue, successive new free-flying-spacecraft concepts can be demonstrated with a high degree of fidelity.



2a. Remote Manipulator System (RMS) in space, with human at its tip.



2b. ARL model RMS with new, human-like, quick, two-cooperating-arm minimanipulator at its end, to capture and manipulate objects under very-high-level command of a human at a distance.

Similarly, for large, very-flexible manipulators, *FIGURE 2,* high precision and speed are achieved via quick two-arm mini-manipulators at the end: Such an "RMS plus human" can capture, and handle deftly, payload spacecraft having unknown dynamics, all in response to high-level, *object*-focused commands from a human (perhaps in shirtsleeves inside the space station).

ARL's free space flyers can also be controlled by GPS (alone!), *FIGURE 1b,* both indoors and out; and they now do formation-flying tasks -- like the interferometric astronomy prelude of *FIGURE 9* -- as will future helicopters in 3D, *FIGURE 8.* (GPS can of course also be the prime member of a sensor set, working with vision, IMU, and others. Using GPS alone was simply a strong proof of a very new concept.)

ARL's deep-underwater research, which has enriched our TRIWG work continually, is done in close cooperation with the Monterey Bay Aquarium Research Institute: At this point, a scientist operating at the surface can call for autonomous station keeping by a robot that uses both vision and the ARL-developed real-time sea-bottom mosaiking in its control loops, *FIGURE 12.* (This underwater research is not part of the TRIWG Program -- but it contributes very much to it; and the new capability may help the Europa mission.) Most recently an operational tethered vehicle used our system to keep station autonomously on a siphonophore (jelly fish) at 200 meter depth.

Each student's project draws deeply on the others, in a continuum of new advances.

A central tenet in ARL's research is that every PhD dissertation must be supported by total-system experiments that (a) have never been done before, and (b) succeed. And each experimental advance must be accompanied by corresponding new advances in fundamental theory. Part II of this report gives a formal abstract of the 46 PhD dissertations; and Appendix A lists all of the publications by ARL student/faculty teams, which of course augment the PhD dissertations themselves.

Table II shows the metric-target achievement of the experimental projects throughout the NASA TRIWG program at ARL. It will be referred to often. Table III offers quantitative estimates of a range of new NASA-mission capability that this set of ARL-developed new concepts may in turn make possible.

This is our contribution to NASA's missions.

PART I. THE FLOW OF NEW CONCEPTS IN ARL

To show this flow of projects, and the fruitful interaction between them -- how they stimulate each other's conception, and how they draw upon each other -- we present here, in **Part I**, a history of the ARL's research for NASA's TRIWG Space Program: the NASA-focused space segment, as well as two other segments -- under water and helicopter research -- from which the space segment has drawn much. Then, as noted, in **Part II** we present a specific, brief abstract of each of the 46 individual research dissertations completed by a PhD student who has graduated from ARL during this program.

Table I gives a list of all the ARL PhD students, with each one's thesis title. The students are numbered in sequence of graduation date, and in the technical narrative of this report their number is noted in [ ]s as their work is discussed. TRIWG funding began in 1985, and Schneider was the first TRIWG-sponsored graduate.

The thesis abstracts are also presented in Part II in the numbered order of Table I. (An N in Table I indicates NASA TRIWG sponsorship. It is also germane to note that the pre-TRIWG work of six students, [4] through [9], was a major forerunner of our TRIWG research: it gave us a strong running start.)

Finally, there is given, in Appendix A, a list of journal and other publications by the student/faculty teams. These have four-digit numbers which will be referred to in [ ]s in Part I and also listed with each author's Abstract in Part II.

The quantitative achievements of each project -- including of course those listed in the *Highlights* on page 3 -- are presented as Metrics in Table II at the end of Part I. Support for the numbers given is to be found in the appropriate Abstract, author's publications, and the dissertation itself.

FIGURE 3. The Flow of New Concepts in ARL

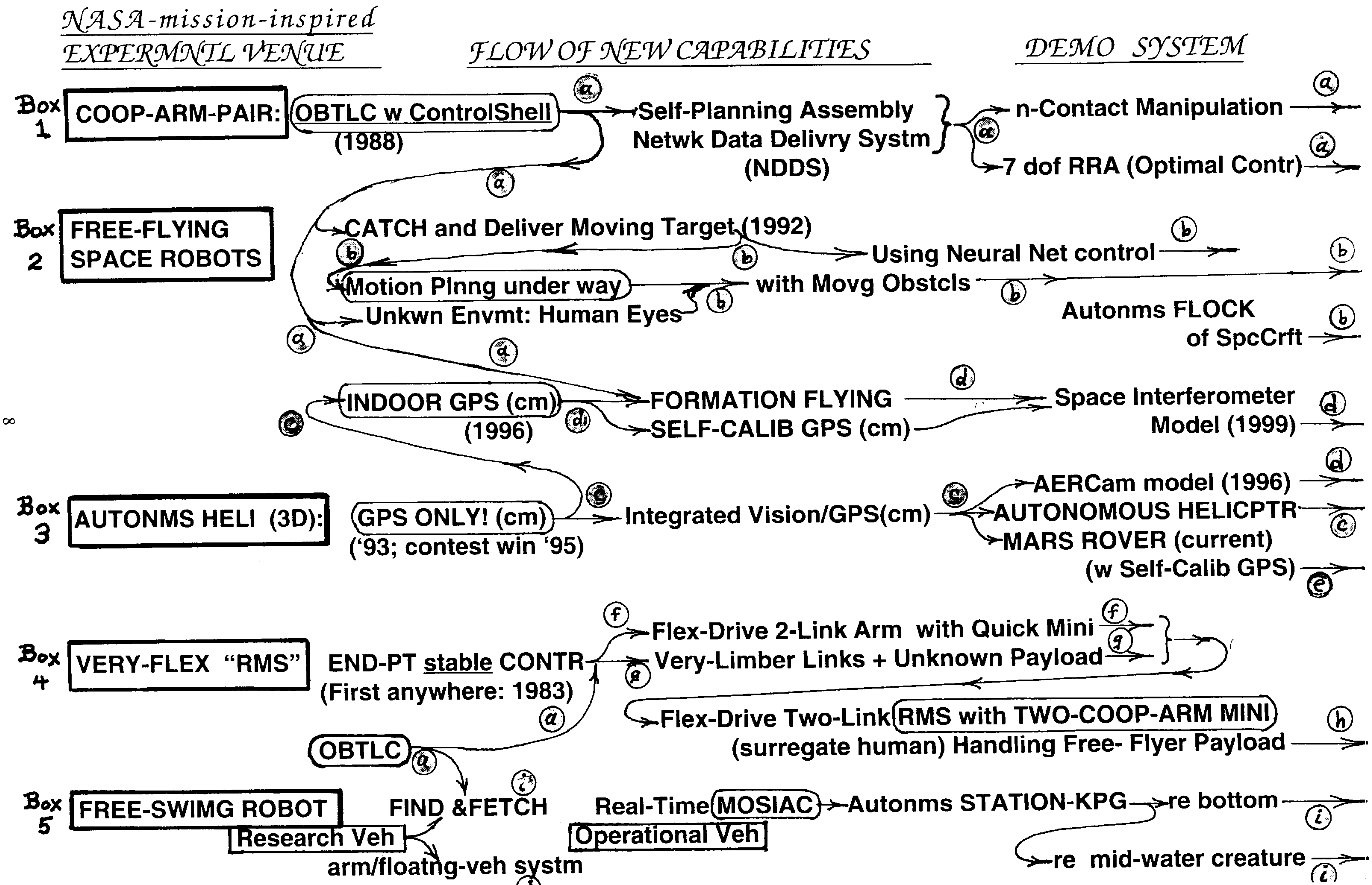
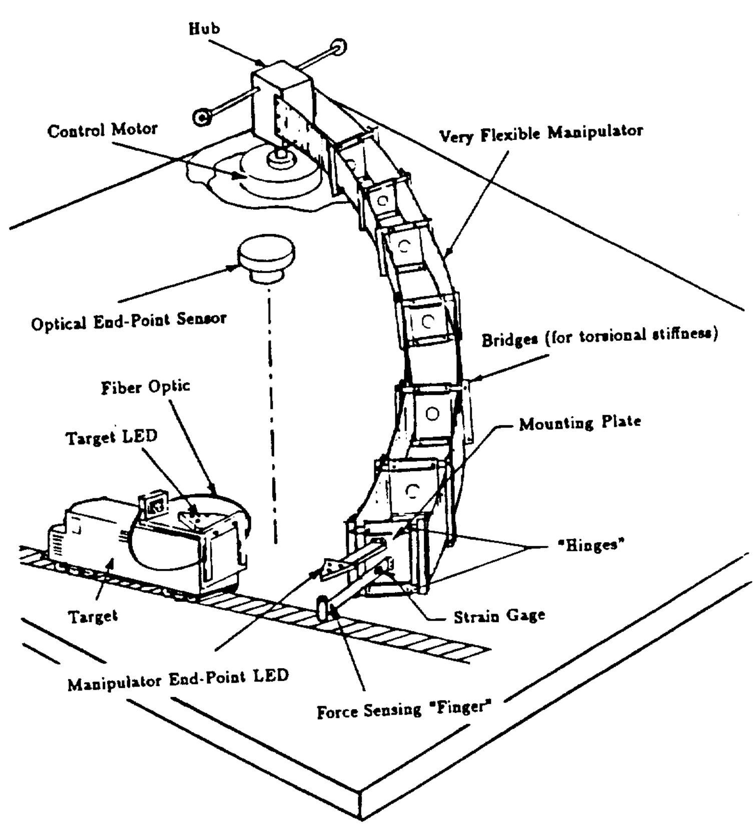


FIGURE 3 depicts the flow of new concepts in ARL, which it is convenient to describe along nine parallel, highly-interacting paths pursued in five experimental venues. The venues are shown as Boxes in FIGURE *3*. The nine broad initiatives, and the paths they have followed, are labeled **a** through **i** in *FIGURE 3*, and described in Sections **a** through **i** below. Along the right side of *FIGURE 3*, page three's *Highlights* emerge.

The experimental metrics achieved in the research of each path in *FIGURE 3* are posted in Table II. Some of the potential metric contributions they may well make to NASA's missions are described in Table III.

ARL's earliest research (Box 4 in *FIGURE 3*) enabled, for the first time anywhere, the precision tip control of extremely-lightly-damped, very-flexible arms like those outside the space shuttle, with the human (inside the shuttle or nearby) commanding the position of the arm's *end point*. This research began in '83 [1038] with the first experiments ever accomplished, *FIGURE 4*, in which control of a limber beam through a shoulder torquer was achieved by sensing the end-point position of its tip directly (non-colocated control,). Both tip position and then tip force were controlled as the tip followed and contacted a moving target, as it was commanded to do [Schmitz 4 ('85) 1038; Maples 5 ('85) 1044]. Many successive advances in this arena will be detailed in Sections **f** and **g**, including a major series of advances using quick minimanipulators at the main arm's tip. First was the work of Chiang [6('86) 1041, 1083]. We'll describe the many successive project steps since then that have now led to the achievement by Schubert, Section **h:** a quick, sizable minimanipulator with two cooperating arms capturing major targets from its place at the end of a large, two-link RMS-type carrying arm, *FIGURE 2* [Schubert 44 ('00) 1170].

FIGURE 4. First-ever control of a flexible arm using end-point feedback.



In parallel with the research on flexible-structure control, we began [Alexander 9 ('85-88) 1052, 1081] a sequence of very new research projects in the high-level control of free-flying robotic spacecraft (Box 2 in *FIGURE 3*). We have developed the capability to emulate very faithfully the zero-g, zero-drag dynamics of space flight in two dimensions: The craft make their own air cushion and operate on a large granite table that is very flat and very level, *FIGURE 1b.* (This approach was suggested by Dr. Ewald Heer of JPL in 1983.) The craft are propelled by small gas jets, and attitude is controlled using on-board reaction wheels. Again, the spacecraft are given a set of object-focused tasks by a human at the strategic level ("Capture that object, and connect it there"): They plan-and-start within one-half second; then plan continuouslly "on the run" to carry out the tasks autonomously. This succession of major advances in free-flying two-arm spacecraft (Path **b** in *FIGURE 3*) is detailed in Section **b**.

Significant advances in Adaptive Control Theory have been integral to *each* ARL project: These will be noted throughout, and reprised in Section **j** at the end of Part I. Some that *focused* thereon include: [Ly 1('83), Rosenthal 2 ('84) . . . .Rovner 8('88), . . . Uhlick 13('90), Zanutta 17('90), Chen 21('92) . . .Wilson 27 ('95). . . Woodley 46 ('00)].

Seven other new-concept research paths -- on which the research in Sections **h** and **b** has also drawn heavily -- are indicated by path labels **a**, **c** through **g**, and **i** in *FIGURE 3*, and described below in Sections **a**, **c** through **g**, and **i**.

As a prelude, an early free-flyer used no propulsion [Jasper 14 ('90)1079]: The spacecraft used its arms to push off from one fixed base, fly freely, and catch itself at another base, as it might to save fuel around the space station. It used an on-board reaction wheel to maintain its proper attitude. (It rotates 180^{o} to approach new dock.)

We proceed now to look in turn at each new-concept path pursued, noting in each case, the metrics that have already been achieved experimentally (Table II) and the possible future metric contributions to NASA's operational missions (Table III).

a **<u>Object-Based Task-Level-Control</u>** [12 ('89), 17, 19, 20, 21, 24, 26, 30, 34, 35, 37, 39, 40, 42, 44, 49] Box 1, and Paths **a** throughout *FIGURE 3*.

A core area of research in ARL's mission has been that of developing [Schneider 12 ('87-'89)] fully generic control architecture for putting the human at high strategic levels -- giving commands that are not about what the *robot* is to do, but about what is to be done with a physical OBJECT: **Object-Based Task-Level Control (OBTLC)**, by Box 1 in *FIGURE 3*. This architecture was developed in ARL, *FIGURE 5*, in the context of a broadly generic robot system -- free-flying or stationary -- having a tightly-integrated pair of fully-cooperating two-link arms: a system with which many tasks involving objects can be done that a one-arm-robot system could never do at all.

This architecture development has been a central enabler in each of the lab's subsequent advances, as will unfold as the range of projects completed and under way in ARL are described briefly below. (Schneider's ARL-developed architecture, known as ControlShell, has also been taken commercial by its inventor and seven other ARL graduates, and is in widespread use. Their company is called Real Time Innovations (2RTI)

The first research with OBTLC was in the control of fixed-base robot arm pairs, *FIGURE 5*, for tasks like unknown-object catch and assembly [Schneider 12 ('89) 1065, 1069, 1075, 1082,]: "Capture that free-flying (spinning) object, and insert it gently into that receptacle." This was a "never-been-done-before" accomplishment with 100% success rate. About 1mm accuracy was required (see Metrics Table II); and the entire task was completed in about 40 seconds.

There followed extension to increasingly challenging tasks: those where the object may have its own dynamics [Meer 26('94)], or the robot base may have local random motions [Vasquez 19 ('91) 1078]. Cogent adaptive control of such systems was advanced by Zanutta [17 ('90)]. If the object vibrated at up to one Hz while spinning, it was readily captured. If the base of the arms had random oscillations of about one cm amplitude, the capture task was completed without requiring measurement of the base motion (feedback control of the arms was quite sufficient). The adaptive enhancement produced excellent control with objects having a wide range of unknown dynamic properties. See Table II.

This concept was then taken to the level of self-organizing assembly in a reconfigurable work cell (top path in *FIGURE 3*), where a task is given, but the location of parts is random and not known ahead of time, and contact manipulation in 3D is required [Pfeffer 24, 1046, 1108; Pardo-Castellote 30, 1084, 1089, 1109, 1111, 1116, 1224, 1129, 1130, 1131, 1133, 1152, 1172, 1173; Sonck 39; 1169]. The work cell used two highly coordinated arms each having "two and one-half" degrees of freedom, that is, full planer (xy) motion plus vertical (z) motion. Some metrics achieved (Table II) and anticipated (Table III) will be discussed.

An important outcome of the reconfigurable-work-cell research was Pardo-Castellote's development [30] of the Network Data Delivery System (NDDS) that has been much drawn upon across the range of ARL projects, and is an important RTI commercial product as well. In particular, it is central in RTI's contributions to the KSC launch processing system.

This OBTLC capability was moved quickly to the arena of free-flying robots carrying two fully-cooperating arms; and that work is the subject of Section **b** which follows this one.

First, on the next pages, we explain a bit more about just how OBTLC functions.

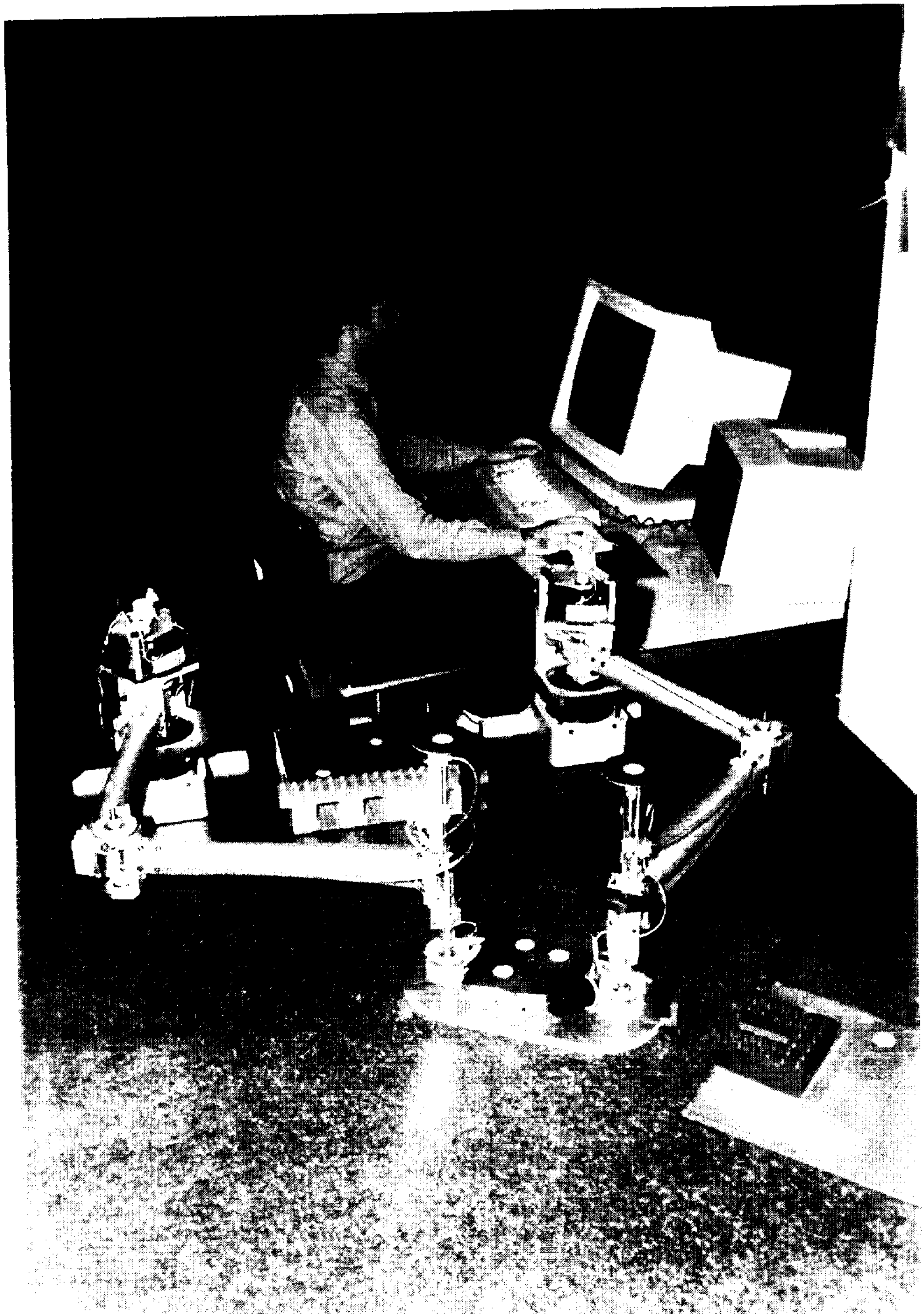


FIGURE 5. The Birth – on a Two-Cooperating Arm System – of the ubiquitous ControlShell Architecture that supports Object-Based Task-Level Control (OBTLC). System show doing an assigned task autonomously: "Capture that object, and insert it into that receptacle."

FIGURE 6. The Concept of Object Based Task-Level Control (OBTLC).

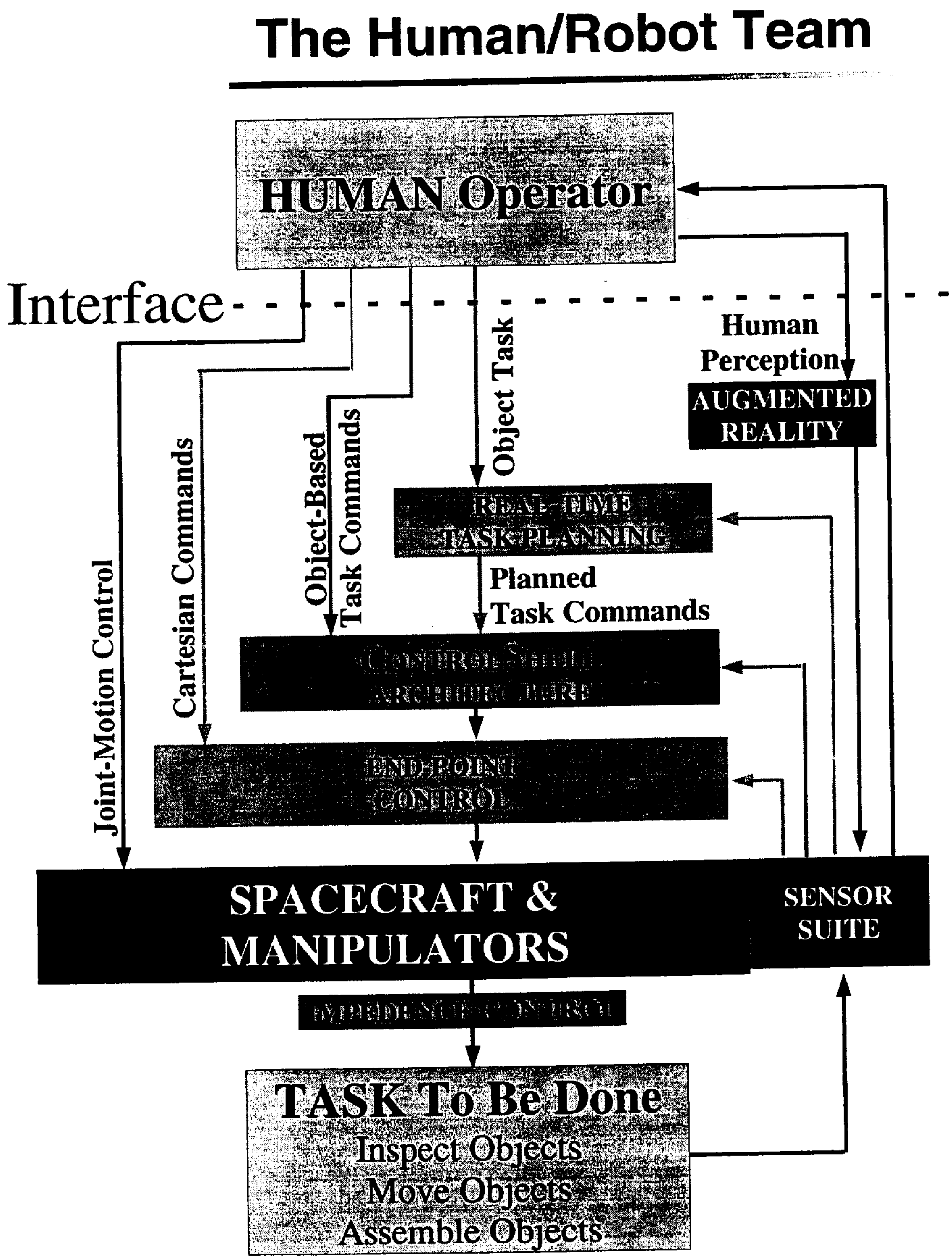


FIGURE 6 is a picture of the new OBTLC concept, and the considerable new power it provides beyond conventional teleoperation. In either case, the human first decides what task is to be done -- perhaps move a chosen object from its present location to a specific new one. With teleoperation -- the left-most path in *FIGURE 6* -- the human then must control the joints of each manipulator, and the thrust on the vehicle that carries it, to first achieve proximity with the object and then to exert forces on it in the sequence required. For a human, such step-by-step teleoperation is extremely difficult, even with just a single manipulator on a fixed base. And it is very fatiguing.

With an OBTLC system, central path in *FIGURE 6*, the human's input simply describes precisely what an object is to be made to do -- perhaps move to a new location and orientation, or connect to another object. The robot then quick-plans what its free-flying base and its manipulator end points must do to act in an optimal way on the object; and it begins moving at once, and replanning continually as it moves. It of course maintains many feedback control loops in the process, drawing on sensors of the location and motion of the object and of its own end points. It uses impedance-matching control to effect gentle contact with objects. The generic architecture for such systems is what Schneider[12] developed [as noted above]. It is an architecture that has been used throughout ARL and in many other venues. The new concept of E. Miles [35 ('97)] is indicated on the right side of FIGURE 6: The human can of course perceive quickly much that no physical sensor can; and this invaluable information can be made part of the "world model" on which the OBTLC system draws in making its decisions.

The quantitative leap enabled by OBTLC is represented by the metric targets achieved in experiments demonstrating its use, that are given throughout Table II. Its potential operational-mission impact is implied throughout Table III -- e.g., controlling AERcam to take the station in space and point as the astronaut beckons it to.

Following its initial demonstration with a fixed-base, two-armed robot, *FIGURE 5*, the next use of OBTLC was to control two-armed free-flying space robots, Section **b** below, and Box 2 in *FIGURE 3*. Its use in task control of other autonomous moving robots -- helicopter, planetary rover, and under-ocean -- are described in Sections **c**, **e**, and **i**. *FIGURE 3* shows these sets of parallel project paths, and how they have drawn so closely upon each other. And the output of path **a** can be seen throughout the startup and flow of the other projects. The metric targets that their experiments met are also given in Table II, and will be discussed as each project is described.

A sequence of six adaptive-control projects with strong, two-link flexible-drive arms having precise quick minis at their tip is described in Section **f** and Path **f** in *FIGURE 3*; and eight projects with long, RMS-like two-very-limber-link arms having mini-manipulator systems at their tip are described in Section **g**. All exploit the OBTLC architecture developed in Section **a**. Its use in the large, flexibly driven RMS carrying a complete two-cooperating-arm minimanipulator system is described in Section **h**. Its use to control a free-swimming underwater vehicle is described in Section **i**.

b **<u>High-Level control of Free-Flying Space Robots</u>** [9,14,20,16, 21,23, 27, 32, 33, 35, 37] Box 2, and Paths b in *FIGURE 3*.

In the free-flying spacecraft arena, each project has drawn heavily on the OBTLC architecture (Box 1 in *FIGURE 3*). The paths pursued begin at Box 2 in *FIGURE 3*. The first task, assigned by Ullman [20 ('89)] to a two-armed free flyer like that in *FIGURE 1*, was to hunt and capture a free-flying (spinning) target, and to place it where told. Next, *FIGURE 7*, it was commanded to do so in the presence of fixed obstacles [D. Miles 37 (96-'97)], and then to do so in the presence of moving obstacles [Kindel '98-'99]. Here, to preplan first and *then* begin the chase is very time consuming and, in the case of the target and obstacles changing course, fruitless: REAL-TIME MOTION PLANNING is essential. This was accomplished first for a dodging target [D.Miles 37('94) 1126, 1143, 1159], and in '98 with moving obstacles as well [Kindel 42 ('98) 1190]: The free-flyer *begins the chase* within a second after getting its task assignment, and thereafter replans continually under way. Replan time < 0.25 sec, even with many moving obstacles that change path, is achieved by a new, highly efficient randomized path planning algorithm that is very rapid. The metric targets achieved in these experiments are given in Table IIb. The speed the new theory gives was also well confirmed in 3D by simulation. Professor Latombe was an important advisor in reviewing this work.

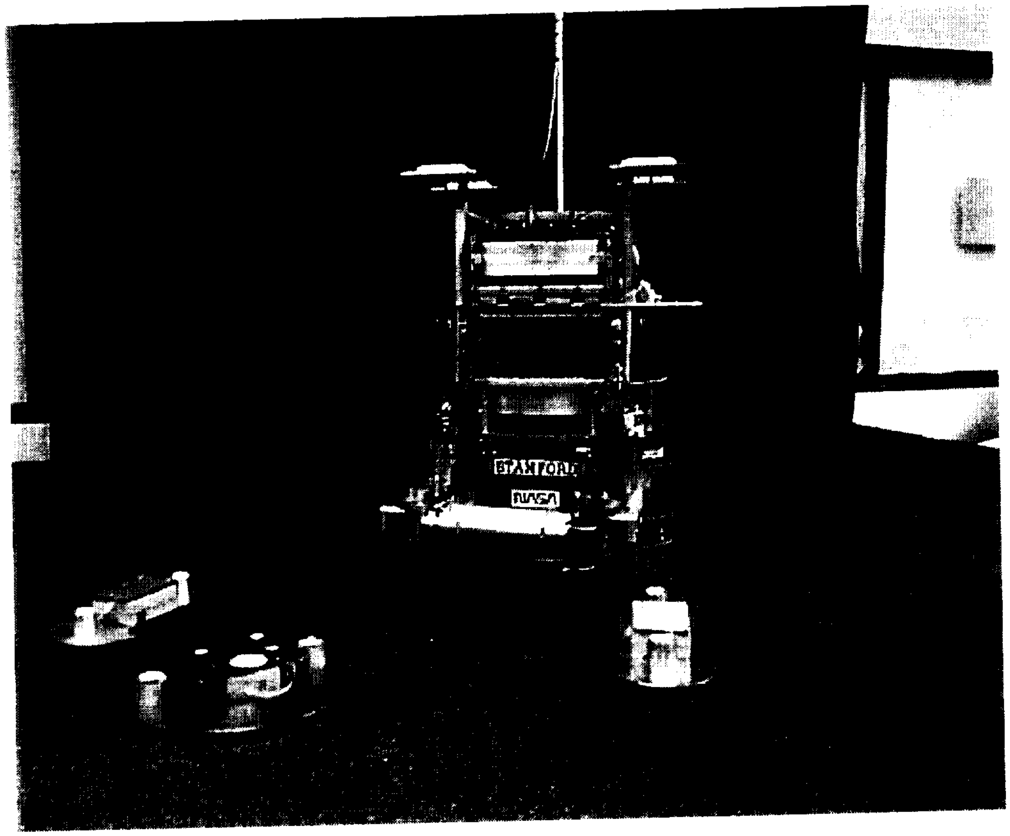
Important very new work was done in '97 [E. Miles 35] in the task-level-control arena wherein the human at high level plays another key role: that of *observing the scene* as only human eyes and mind can, and continually correcting and enriching the (free-flying) robot's *in situ* model of its environment in real time. This is represented by the "human perception" path along the right side of FIGURE 6. The first experiments have already demonstrated the power latent in this extension of task-level control:Table II b.

Once found and captured, manipulation and delivery of objects of unknown physical properties has also been well demonstrated [Ullman 20 ('92), Koningstein 16 ('90), Chen 21 ('92)].

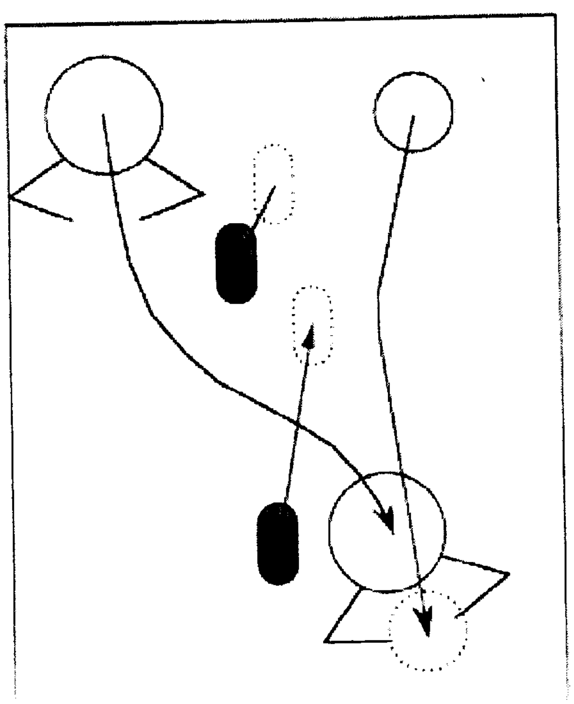
Early work [Dickson 23 ('93), Russakow 32 ('95)] was also done with *<u>two separate</u>* two-arm free-flyers cooperating to do a task: eg, handle a long beam, connect it to another or insert it as assigned. In these experiments, one spacecraft was named the "foreman" who planned what the two would do together. Later ('97) work was begun with high-precision formation flying of spacecraft, *FIGURE 9*, as will be required, for example, for km-wide-based interferometric astronomy from space [Corazzini 41('00), Robertson 45('00), 1166]. This, and the station-keeping precursor work of Zimmerman, all using indoor GPS are described in Section **d** below. This research was all completed under the current TRIWG grant. Experimental metric targets achieved are given in Table IId.

We plan next to work with a *flock* of craft that, assigned a task to do as a group, will *organize themselves* to assess the situation on site, perhaps revisit details with the

FIGURE 7. Free-Flying Space Robot with OBTLC, using Real-Time Planning under way, to acquire a dodging target amid moving obstacles.



a. Experimental System (similar to Figure 1b.)



b. Human's screen for controlling from high level: "Capture that object; and don't hit any others."

human, and then carry out the desired, object-focused task. We plan to work first with air-cushion vehicles in the lab, and then with very small helicopter aircraft [Moraleda 52, Clark 56]. This work is sponsored currently by a follow-on NASA grant to ARL.

c **Autonomous-Helicopter Control with GPS (Only!)** Box 3 in FIGURE 3

In '93 a helicopter project, Box 3, was undertaken: A national contest required a totally autonomous air vehicle to snatch a small disk from a six-foot ring on one side of a tennis net and deposit it in a similar ring on the other side. These goals had never been achieved in four years of contest trying. Then our team went to Atlanta in '95 and won the contest.

The key was developing a new, GPS-receiver-based system (using carrier-phase measurement) that would control precisely both the location (a few cm) and attitude (three degrees) of an inherently very unstable helicopter [Conway 31('95)1137]. No other sensor was used. *FIGURE 8* shows the helicopter with four 3" square antennae. Another is fixed to the ground as a differential reference. The guidance accuracy achieved is given in Table IIc: about 4cm and 6^{o}. (Dr. Conway went next to the Genome project at the Stanford Medical School, where he set up data-management systems. Then he set up a new start-up company: Silicon Genetics.)

This helicopter project was initiated (for its first year only) under TRIWG support. Thereafter, all of our helicopter work has been supported by a grant from the Helicopter Group at NASA Ames (none from TRIWG). However, our seminal work with GPS-only control of an unstable air vehicle -- to cm level accuracy -- is being drawn on continually, Paths **c** in *FIGURE 3,* for a broad range of NASA-focused projects, as the next two sections will illustrate. That happened fast. We chose this as the place in our report to describe our helicopter GPS system to make its adoption by other projects easy to follow.

Meanwhile, the current helicopter work will combine GPS and stereo visual sensing to execute such strategic assigned tasks as hovering over an evasive ground vehicle, or snatching a target from it, using a helicopter with sling [Frew 50, 1177, 1184]. It will be important, at an early stage, to fuse independent inertial measurement units into GPS-guided helicopters, to provide smooth continuity when there are temporary signal dropouts from GPS and vision units.

FIGURE 8. Totally autonomous helicopter using GPS (only!) to sense location and attitude, and carry out complex object-focused tasks. (Won international Autonomous Helicopter Contest in 1995.)

d <u>**GPS-Based Control of Free-Flying Space Robots**</u> [33, 41, 45] Paths **c,d,e** in *FIGURE 3*.

As with many concepts conceived for one project in ARL, GPS was promptly drawn upon by one more after another, Paths **c, d, e** in *FIGURE 3*. First, the free flyers on the table indoors were given an indoor version of GPS: Path **cd**. A constellation of Pseudo satellites, or <u>Pseudolites</u> were installed on the ceiling (with frequencies identical to those of the national orbiting system). Tasks like catching a flying object (*FIGURE 1b)* and keeping station on another vehicle using no sensing except indoor GPS were achieved by Zimmerman in about '95 [33; 1113, 1123, 1141, 1163], with navigation accuracy of 2cm, 3 degrees, and station-keeping accuracy of 4cm; 8

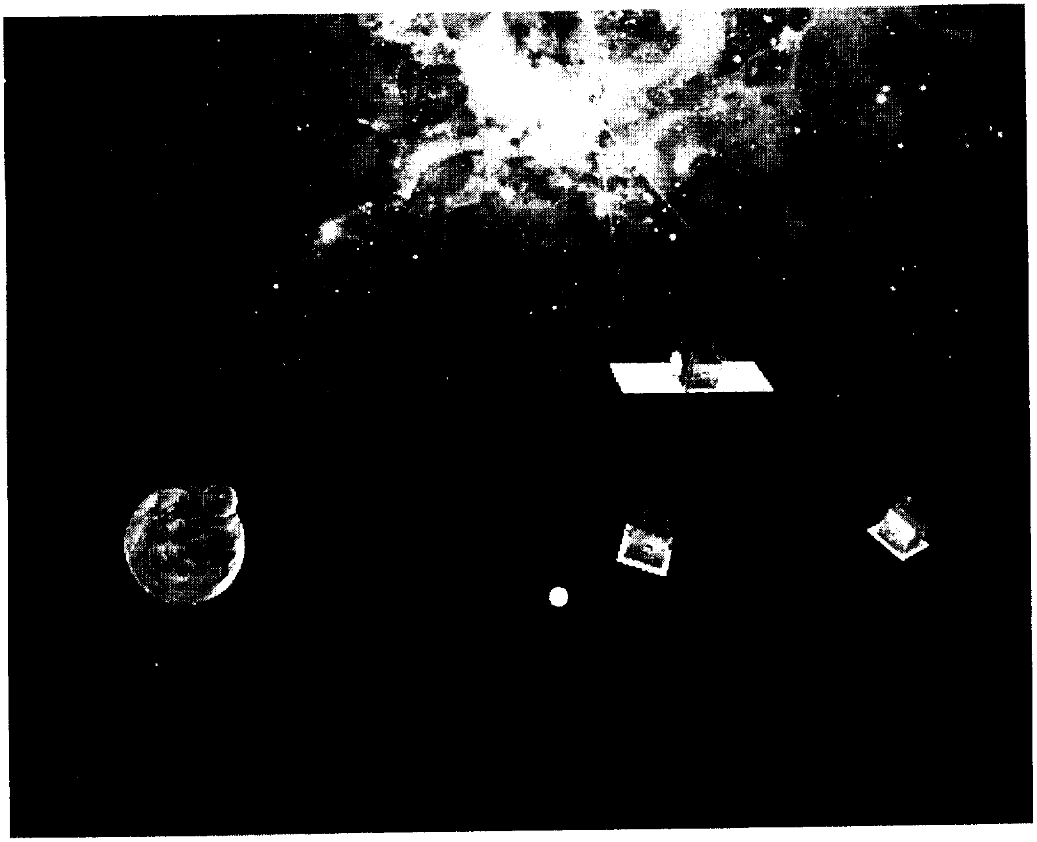
degrees, Table IId. Two major new problems with the indoor system that had to be solved were multipath geometry, and the "near-far" problem of such close transmitters.

This capability has obvious ubiquitous future use for semi-autonomous free-flying vehicles in the vicinity of the space station. The AERCam, which NASA flew from the Space Shuttle in 1998, is the first of these. It is a beach-ball size free flyer carrying stereo live video. An astronaut can call for its presence anywhere around the space station to provide an added view from a different vantage point. In its first flight, the AERcam was teleoperated by another astronaut inside the space shuttle. In a next step, Zimmerman's GPS-based control scheme could make AERcam a semiautonomous vehicle which the astronaut can simply instruct to "Go to that location (pointing) and give me a view of that area, from 3 meters away," and the OBTLC system will carry out the assigned task autonomously, planning as it goes to avoid obstacles and astronauts. Section A of Table III describes quantitatively the major jump in AERcam's capability that the combination of ARL's contributions -- OBTLC and pseudolite GPS -- could make. The development team at Johnson Space Flight Center is developing such a system for the AERcam. Key achievable metrics are given in Table IIId. They look quite worthwhile. Both Space-Station-mounted pseudolites and the earth-orbiting GPS are likely to be used. And it will be important to integrate an inertial measurement unit into all space free flyers, to provide independent continuity when there are temporary GPS receiver dropouts.

ARL graduate Zimmerman, whose PhD research, described above, included development of the indoor pseudolite system for the free flyers, is now part of the team at the IntegriNautics company building commercial pseudolites, and supported by the FAA to develop precision landing systems with cm accuracy to be deployed nation wide. (High-precision farm tractor navigation has also been developed in Professor Parkinson's definitive GPS Laboratory at Stanford University. The economic payoff there is also substantial.)

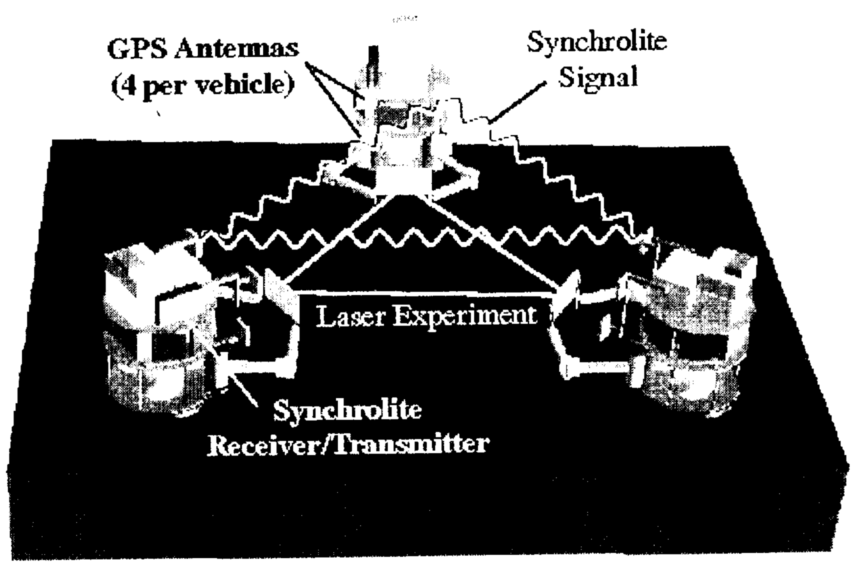
Interferometric Astronomy [41, 45], Path **ce.** Another current ARL project using pseudolite GPS is to demonstrate, *FIGURE 9b,* an experimental model of a precision formation-flying task in deep space, *FIGURE 9a*: There, three optics-carrying spacecraft a few kilometers apart will do interferometric astronomy that requires extremely precise alignment and station keeping between them. For spacecraft that are far from the earth-orbiting GPS system, the new concept being developed by Corazzini in ARL is **self calibration** among pseudolite sending/receiving systems -- transceivers -- on each of the three spacecraft She has now completed experimental testing of this new capability. [41('00), 1179]. In total, there will be needed three successive levels of precision: Self-calibrating GPS (Corazzini), inter-spacecraft laser optics [Robertson 45('00)], and astronomy optics. The first two have now been tested as a system in ARL [1176], with metric performance of 1cm and 2deg for GPS alone; 1 mm, 0.01 deg with laser (Table **IId**).

FIGURE 9. Interferometric Astronomy from a Precision-Controlled formation of Spacecraft.



a. In Space: nominal baseline of order one km.

b. On ARL's granite table (air bearing); baseline of order one meter.



First-Ever Self-Calibrating GPS System controlling relative location of three formation-flying interferometer spacecraft to one cm (and orientation to one degree) in laboratory. Should achieve same accuracy in space, independent of baseline length. (Telescopes then work from there down to a small fraction of the wavelength of light.)

e **GPS Control of Planetary Rovers** [51, 54] Path **e**, lower right in *FIGURE 3*

For planetary rovers capable of autonomous strategic-task execution at cm-level precision, a *comparable* ***GPS self-calibration*** *concept* is being developed by LeMaster [51]: The rover will place mounted pseudolite transceivers at strategic locations around that area on the planet where it will be working. The pseudolites-plus-rover system will then carry out the multiply-redundant set of measurements to self calibrate itself to the GPS carrier-phase level of accuracy -- about 2 cm [LeMaster 51, 1182, 1185, 1189]. Parallel work by Ni [54] is studying special video triangulation techniques to be fused with the GPS/pseudolite system. This research may provide a basis for valuable components for future rovers, where very precise location has high scientific importance.

f **High-Level (OBTLC) control of Strong, Flexible-Drive Two-Link Arms with Quick Manipulator at Tip** [10,11,13,15,24,30.] Path **f** in *FIGURE 3.*

Research with two-link arms, Path **f** was begun in '85, first with very-flexible-joint torquing systems [Hollers10 ('88), Uhlick 13 ('90)], which could do very rapid, adaptive pick-and-place of heavy objects of unknown mass. Then extensive research with two-very-limber-*beam* manipulators began in '89; the flex-beam work (Path **g**) will be described in Section **g**, which follows this section.

Focus on redundant two-flexible-link systems -- large arms with a quick mini at the tip -- was begun about '87, for the combined purpose of both (a) covering a large area, and then (b) doing quickly, extremely precise tasks in a local area. The first phase of this work used, as the carrying links, *rigid ones with flexible drive trains* at each joint. Such demonstrations as "Move along that complicated surface contour with a normal force of x Newtons," and "Move quickly over the table and make firm contact with that thin vertical stick of dry spaghetti; but don't break it!" were accomplished with high reliability [Kraft 11('89), Andersen 15 ('90)]. (Similar minis at the end of *very-limber* beams are described in Section **g**.)

Later, in the '90 - '93 time frame, a factory work cell with two cooperating two-link arms (having flexible drive) was built by Pfeffer [24 (93)] to carry out assemblies of parts from increasingly high levels of command: path across the top of *FIGURE 3.* First [24] the system of arms was to follow -- autonomously -- the command to assemble a fragile neon tube into its socket -- and turn it on! It did! Next, under Pardo-Castellote [30 ('95)], as it assembled a number of parts, the arm system decided, itself, in which order to do assembly, depending on which order the parts came on a belt, and where each arm happened to be as they arrived. This work of course drew heavily on the generic ControlShell architecture developed in ARL (see Section **a** above). It is also giving rise to increasingly sophisticated generic data-management architecture, beginning with the Network Data Delivery System (NDDS) [Pardo-Castellote 30 ('95)] which has also now been commercialized in the same company as ControlShell, Real Time Innovations. This work was sponsored by DARPA and NIST.

More generally, redundant robot systems are a superior way (and sometimes the only *possible* way) to carry out tasks where the environment is restrictive or dynamic -- as in reaching around behind one moving object to capture another, or in minimizing task time or effort via pose selection. A more general study of strong, 3D redundant robot technology has been carried out by Hunt [40('00)]. He worked with a 7 dof Robotics Research Arm (not flexible drive) at NASA Ames to develop a new (OBTLC-based) generic method for blending the multiple objectives of task space and null space to set priorities, given the various tasks the robot is to perform, and thereby to produce continuously-optimized system performance. Paths **a** at the top of *FIGURE 3.*

g. Quick End-Point Control of Very-limber-Beam Two-Link Manipulators

[4,5,6,8,18, 22,25,36] Path **g** in *FIGURE 3.*

Throughout ARL's history there has been -- in parallel with its work with free-flying space robots -- a continuously advancing pursuit of the very precise control of very flexible manipulator systems that will characterize large robot arms attached to space stations, of which the Space Shuttle RMS is the prototype. From the beginning of ARL, and constantly, this work has generated a sequence of fundamental advances. The first-ever demonstration anywhere of (non-colocated) tip-position control of a lightly-damped, very limber beam [Schmitz 4 ('84), 1038], was the beginning. The beam, like the shuttle arm, had a natural period of six seconds. The system wanted insidiously to go unstable: Astute modeling was the key to controlling it very well.

In the next experiments, *FIGURE 4,* the beam tip measured optically its distance from a moving object -- a target -- and followed its instructions to chase the object and make and maintain gentle contact with it [Maples 5 ('85), 1044] -- also a first.

Next, *FIGURE 10,* a quick minimanipulator was affixed to the long arm, [Chiang 6 ('86),1041,1083], Now it could do very precise motions much more quickly, like snatching objects from one spot and placing them exactly at another. This, too, was seminal work that began a long sequence of new advances based on this powerful redundancy concept, as will be described three paragraphs hence.

In '87 an important generic advance was made in adaptive control: A very robust very-

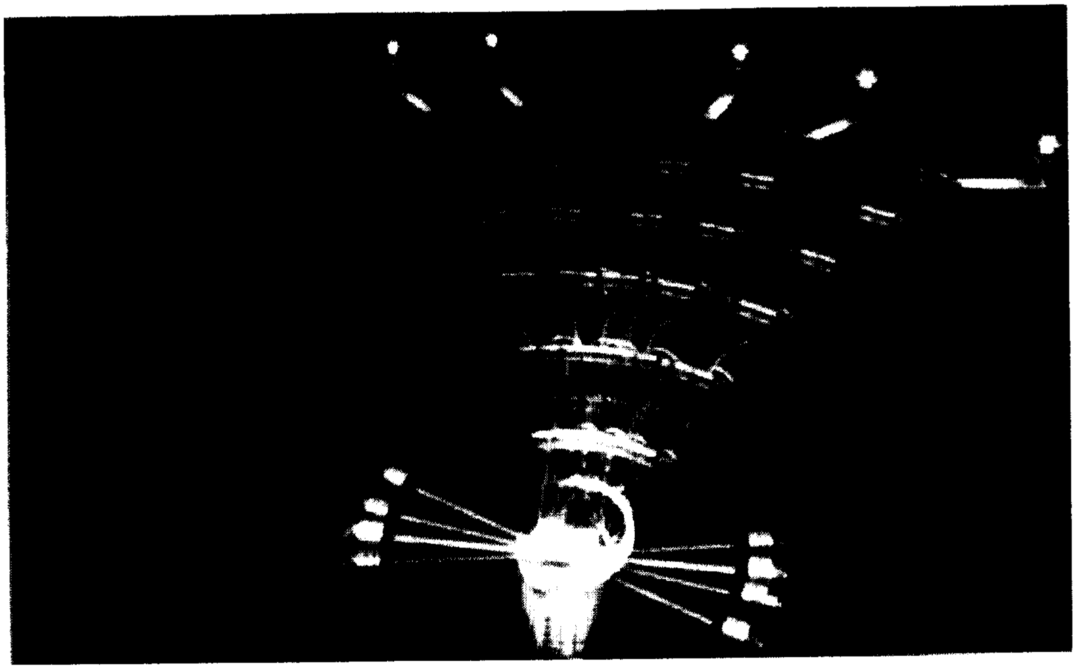
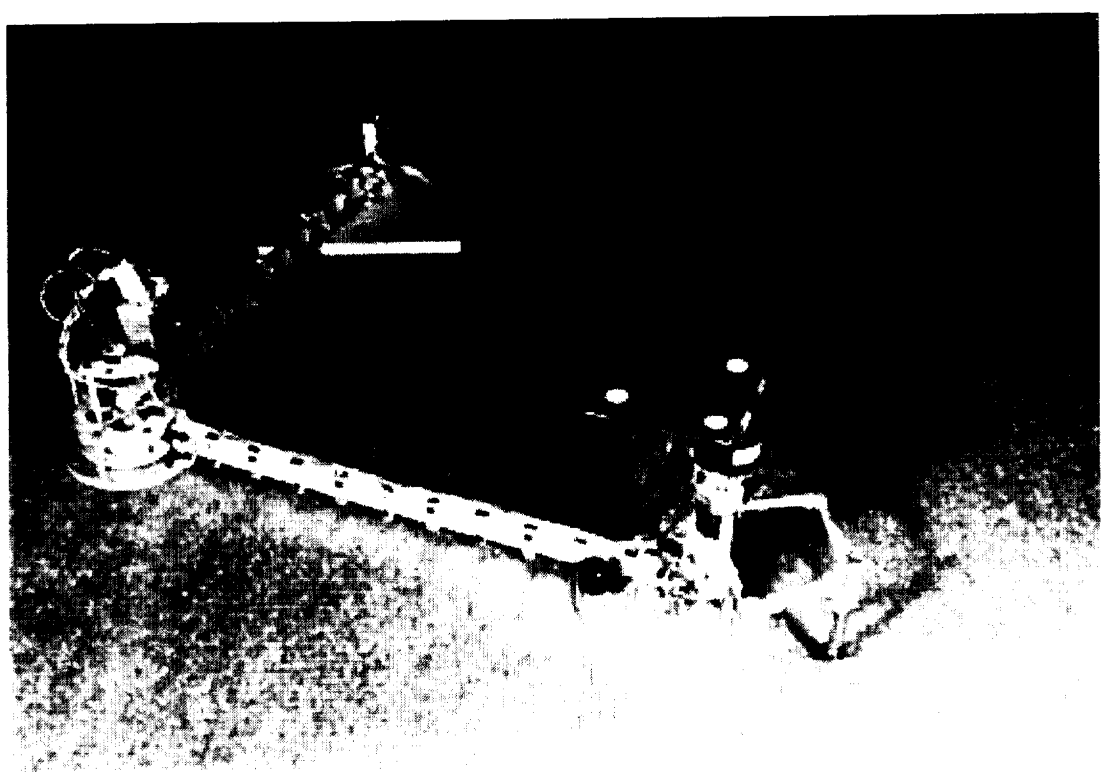


FIGURE 10. Early research with very flexible manipulator carrying very-quick mini at its tip.

FIGURE 11. Two-very-flexible-link manipulator carrying two-d.o.f. mini. The system covers a large area with the large manipulator having a two-second natural period; then carries out precise (mm) local position and push tasks with five Hertz bandwidth.



limber-arm system was demonstrated that could pick up an object of unknown mass, assess the mass in less than a second, and move it quickly to an assigned new place using high control gains that would have produced highly-divergent instability if the mass had been estimated incorrectly [8 ('88)]. D. Rovner, who was awarded his PhD for this work, then was given full responsibility for flight control of the Pegasus air/space craft that was dropped from a B-52 and propelled itself into orbit 18 months after his graduation. That was the first flight of Pegasus, and a totally successful forerunner of many to follow.

Adaptive control capability was later advanced by Alder to where the inert mass was replaced with a captured object having unknown dynamics of its own, like a captured spacecraft with a large, flexible solar array, or with fuel sloshing inside [Alder 22 ('93), 1086, 1094, 1096, 1102, 1160]. By '95 this had been extended by Imms to a captured mass having unknown, two-degree-of-freedom dynamics. Very strong control was achieved very quickly (about one second).

Research with flexible two-link arms was begun in '85, first with very-flexible-joint torque systems, Section **f**, and then in '89 with two-very-limber-link systems. For the latter, an important breakthrough was Oakley developing the power of a total modal model for the entire system, rather than by combining adjunct models of its links. First-ever experiments were done in 2D, simulating zero-g very well by supporting the joint and tip on air bearings [Oakley 18 ('91), 1063, 1070, 1071, 1074, 1077, 1080].

Focus on redundant two-flexible-link systems -- two main links plus a mini at the tip -- was begun about '87, for the dual purpose, again, of both (a) covering a large area, and then (b) doing quickly, extremely precise tasks in a local area. The first phase of this work used, as the carrying links, rigid ones with flexible drive trains at each joint, Section **f**. As noted earlier, such demonstrations as "Move along that surface contour with a normal force of x Newtons," and (from a meter away) "Move quickly above the table and make firm contact with that thin vertical stick of dry spaghetti; but don't break it!" were accomplished with high reliability [Kraft 11('89)1054, 1083], [Andersen 15 ('90)].

A more recent sequence [Ballhaus 25('93), Stevens 36 ('97)] of ARL research on large two-very-limber-link manipulators in space has used air-cushion support of the primary joints to match the zero-g, zero-drag dynamics of space operation, *FIGURE 11*. Drawing on the considerable research (some 10 PhD projects) on control of very limber beams and of two-link flexible-drive-train robots with tip minimanipulators, this research has concentrated on manipulators having long, two-link very-limber beams with two-degree-of-freedom minimanipulators at their tips; again, to both cover a wide area, and then execute delicate local tasks in 2D quickly with high precision of, first, position [Ballhaus 25 ('93), 1088, 1092, 1094, 1099], and then force control [Stevens 36 ('97), 1114, 1154, 1175] in capturing a free-in-space object. The large-limber-beam system had a natural period of about *6 seconds* (depending on the link configuration), while the mini had a bandwidth of *several Hertz*. The dynamics of astutely controlling, this total system, with its very useful redundancy, led to making major additional

fundamental advances. And this, in turn, led finally to the major new project that will now be described.

h **Large RMS-like arm with quick, two-arm mini at its tip.** Path **h**, lower right in *FIGURE 3 (on page 4).*

The current space-arm project [Schubert 44('00), 1170] shown in FIGURE 2 goes an important step further: The manipulator *at the tip* is a human-like two-arm system, which makes it an interesting first emulation of the current Space Shuttle RMS (remote manipulator system) arm *with an actual human at its tip.* For certain task areas the real human could stay inside (at great improvement in safety and cost), and simply give high-level object-focused task commands to the large-carrier-arm/mini-arm-pair system, watching and intervening occasionally, as necessary.

For any task, the two-arm-manipulator system could not be operated by a human inside the space station nearly as well at the joint-command level as it can at the task-command level, we are finding: Again, the ARL system is one that draws importantly on the OBTLC architecture portrayed in *FIGURE 6.* Moreover, there is full two-way dynamic coupling between the large-arm motions and the motions of the mini-arm pair -- greatly accentuated if the arms have just grasped an object having substantial inertia. This project represents a major theoretical and experimental advance in the control of the space-station-based manipulation system. It has drawn heavily upon the considerable range of experimental work that has preceded it in ARL, as Paths **f**, **g**, and **h** in *FIGURE 3* make quite clear.

Specifically, a new method was created for choosing impedance control parameters in end-point operational space, combined with redundant-degree-of-freedom management, to enable quick, two-arm moves with gentle contact on an object or on the environment. Experiments (*FIGURE 2)* included capture and manipulation of free-flying objects, manipulation and insertion of a flexible object, and maintaining specified force on an accelerating object.

i **Precise High-Level Control of Under-Ocean Robots and Optical Mosaiking** [28, 29, 34] Path **i** in *FIGURE 3.*

ARL's work as an invited partner with the Monterey Bay Aquarium Research Institute (MBARI) began about 1994. This program has been totally under the direction of Professor Steven Rock from its inception. A primary first concept was extending the space-based OBTLC control architecture to three-dimensional free-swimming vehicles under the ocean. The first project in this series, completed by Wang in '96, was for the ARL free swimmer (OTTER), shown in *FIGURE 12*, to follow the assignment: "Search for and find a given object, pick it up, and deliver it to a specified tank-edge spot." It did. [Wang 34, ('96), 1093, 1106, 1125, 1126, 1146, 1151, 1153, 1155, 1156, 1173].

All of our work with MBARI is now supported by the Packard Foundation. However, the first-year running start was made possible by extending our TRIWG work to the underwater arena; and the synergy for both programs has been a very strong two-way win.

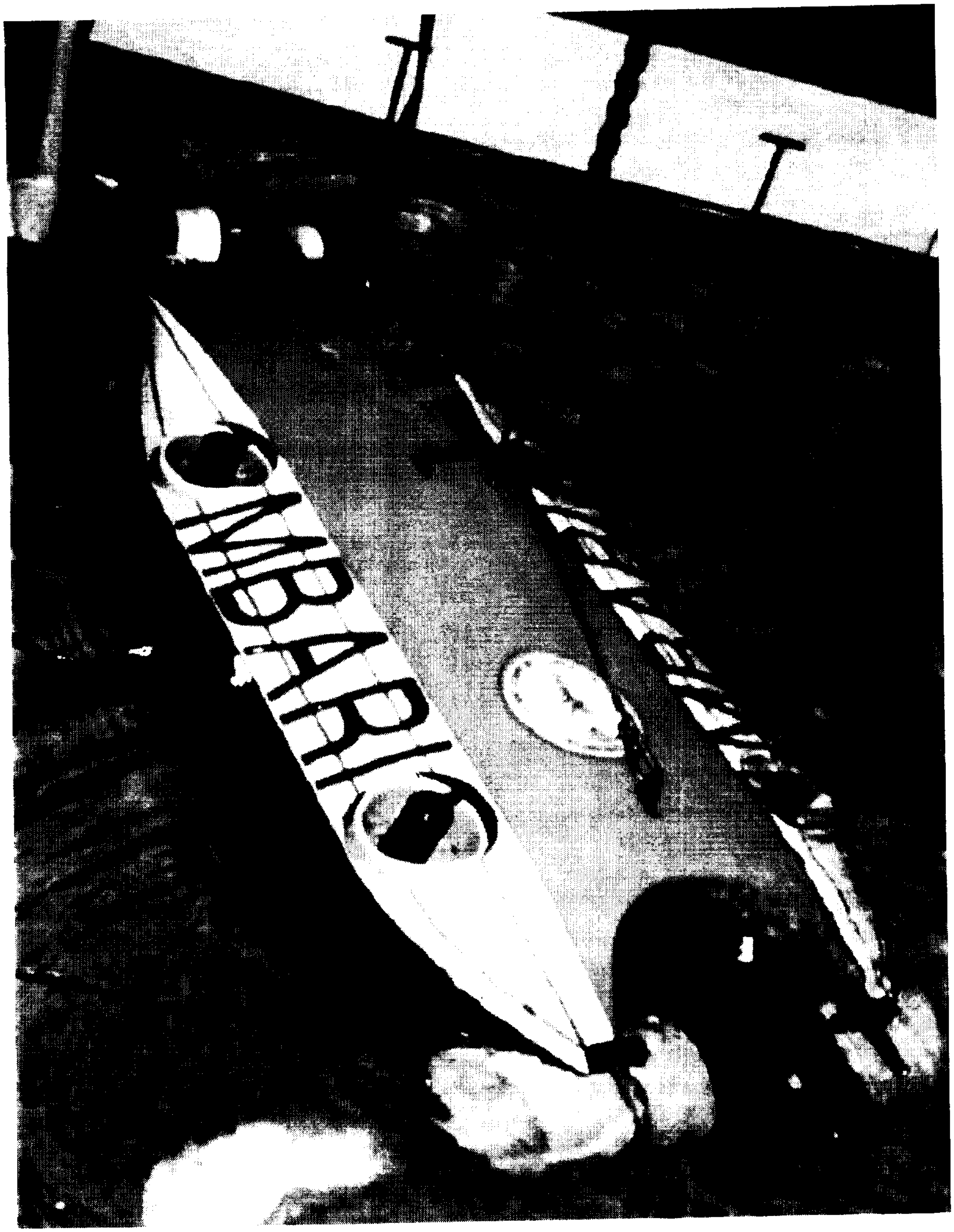
The next project, by Huster 49, will be to extend Wang's concept to grasping and insertion operations, with objects on the bottom or in a sea wall, from a free-floating robot [1180]. He is starting with a 3D RRC simulation at Ames, and will move then to OTTER and to the operational (tethered) robot near the sea bottom beneath MBARI's ship. It will become a valuable new operational capability for ocean scientists.

Simultaneous with Wang's work, a remarkable ocean-floor mosaiking system was developed by Marks, that covers each 20"x30" area in under 3 minutes. Composites of these mosaics in turn become a basis for precise navigation relative to objects of scientific interest over a wide area. The system is now in regular use in the MBARI operational ocean-floor tethered-robot system, relieving manual operators from keeping station over interesting objects for long periods [Marks 28 ('95)]. The current research by Fleischer extends the mosaiking to large areas, with high accuracy through self checking, to enable execution of high-level commands (1) For navigating to -- and keeping station on -- bottom objects seen earlier in the exploration mode [Fleischer 38 ('00) 1168, 1171], and (2) To demonstrate use of concept (1) in grasping and insertion operations from a floating robot [Huster 1180]. The metrics achieved are striking, Table 1 i.

Another sequence of underwater projects is to learn deeply (for the first time anywhere) the <u>transient</u> hydrodynamics of an underwater-arm/underwater-vehicle *system*, and to control such with great precision. This was completed first for a free-floating vehicle with a one-link arm by McLain in '95 [29, 1145, 1150], and since then, has been under way for two-link arms by Leaborne [43, 1181]. This turns out to be <u>very</u> uncharted research territory: unsteady fluid motion about cylinders having barn-door-like motion back through their own path has simply not been studied. Understanding it is of course essential to the very precise control of the tip of an underwater manipulator on a free-floating vehicle that will be so valuable. Excellent performance of such a vehicle with a single-link arm was accomplished by McLain using feedback of both vehicle and arm position plus feedforward based on the hydrodynamic model he developed. Leaborne has extended this elegantly to a two-link-arm/floating-vehicle system, of which her model enables excellent control.

The newest project ARL is starting with MBARI is to provide a free-floating vehicle that will simply keep station for a long time on a midwater organism of interest, taking

FIGURE 12. OTTER, the ARL underwater craft to demonstrate the carrying out of semi-autonomous tasks commanded from very high level, using OBTLC with selected manipulator systems. Research done jointly with the Monterey Bay Aquarium Research Institute (MBARI).



photos, say, every 20 minutes, and relaying them to a laboratory on shore. It may ultimately, when asked, insert dye at the siphonophore's intake, for example, and take the desired time series of photographs to study the ensuing process.The first test of an ARL system designed to do this task was conducted on 2 August '00 with the operational deep sea (tethered) robot at MBARI. It maintained lateral station robustly on a jelly fish at 200 meters depth. (Keeping distance from creature --- about one meter -- was maintained by the human pilot. in this test.) It is an excellent start in one more new research direction.

j <u>Ubiquitous Fundamental Research in Adaptive Control</u> [1,2,3,7,8,13,17, 19,21,22,27. Also present in nearly every other project.]

A path of fundamental research in adaptive control theory began at the outset of ARL, and has continued, thoroughly embedded in ARL's other projects, throughout its history. Some examples are given here.

The first work was in extending basic optimal control theory for the first time to beget optimization over a *range* of parameter values [Ly 1, 1033, 1040], thus greatly increasing the usefulness thereof.

Early work in robust adaptive control with hi-Q, four-disk systems [Rosenthal 2, Sidman 7] preceded the first strong control of a very limber arm with unknown mass at its tip by Rovner [8], Section **g**. Learning time was about one second. This was followed by control of a very limber arm carrying a payload having unknown dynamics [one dof by Alder 22, 1086, 1094, 1096, 1102, 1160; two dof by Steven Ims 47]. Carried out in parallel was research with a flex-drive two-link arm with very large changes in payload mass [Uhlick 13; see his Abstract in Part II].

Adaptive control of a <u>pair</u> of two-link arms is reported in [Zanutta 17 and Vasquez 19], and of such a pair on a free-flyer in [Chen 21]. (Again, see Abstracts, and the publications each lists, in Part II.)

In 1995, astute hybrid neural-network control was developed for a two-arm free flyer, and fundamental new insight was proven about exactly when and how this technique has potent generic robustness advantages (and when it does not) [Wilson 27 ('95)].

Current research is exploring how viable physical models can be inferred in terms of behavioral measurements *alone* [Woodley 46, 1137, 1161, 1162, 1165, 1177, 1178, 1184, 1187].

In Summary

A summary of some Highlights of ARL's part in NASA's TRIWG Program was given on page 2. The pages that followed describe the sequence and flow of projects that made them each possible.

The NASA TRIWG Program at Stanford's Aerospace Robotics Laboratory has been a source of professional pride of accomplishment for the 40 PhD students, three faculty, and three staff members who have been a part of the ARL during the 15 years through which about half its research, and 23 of its 46 PhD graduates, have been supported by the Program. The TRIWG Program had much to do with the strong, healthy PhD laboratory at Stanford that is ARL.

And ARL Director Stephen Rock is leading it in very exciting new directions, of which space research is a very important part (drawing upon Paths **b, d, h** in *FIGURE 3*), as is very new work in free-swimming robots (Path **i**).

Professors and Staff in the Stanford Aerospace Robotics Laboratory

The three professors who have the led the NASA TRIWG Research Program at Stanford are given on the cover of this report. Robert Cannon began the ARL in 1983. He was principal advisor to the first 21 PhD graduates in Table I, and to about one half of those graduating between 1992 and 1997. (Each student's advisor is given with the dissertation abstract in Part II of this Final Report.)

Stephen Rock came to Stanford in 1989, became principal advisor to half the students graduating between '93 and ''97 and has been principal advisor to all but four graduates since. He has been ARL's primary thesis advisor since 1997, and has been the sole leader of ARL's work with the Monterey Bay Aquarium Research Institute from its beginning. He is now the Director of ARL.

Jonathon How came to Stanford in 1994, and has been principal advisor to five of the ARL PhD graduates in Table I (and to a number of others). He brought wonderful energy and insight for new research directions. For personal reasons, Professor How moved this year to a faculty position at MIT.

Stanley Schneider [12] held a post doctoral appointment from '90 to '92, and provided extremely valuable ARL leadership at a formative time. Earlier, Harold Alexander served in a similar important role in the new laboratory.

Throughout most of ARL's life, Gad Shelef has worked, with great skill, as a designer and as a mentor, to help each student design the mechanical system for his or her experiments, and has overseen the machining and construction of its parts.

Godwin Zhang has provided great insight and remarkable capacity to design and maintain the electrical and electronic subsystems for PhD student experiments. He has typically been called upon by five or six students concurrently, and never left any waiting; and the systems had little down time.

Jane Lintott managed ARL's resources: flawless student and staff financial support management; purchase of capital laboratory equipment with precision; and preparation of well-documented proposals for each new laboratory support increment. She has also produced for publication all of the laboratory's technical reports.

TABLE I

ALL THE PhD GRADUATES OF
STANFORD UNIVERSITY'S
AEROSPACE ROBOTICS LABORATORY

(3 Pages)

TABLE I

PhD GRADUATES OF THE AEROSPACE ROBOTICS LABORATORY

Year		Graduate	Project in Lab (Thesis Abstract in Part II)	Subsequent Professional Path
1. 1983		Uy Loi Ly	SANDY Robust/Optimal Design Code	Univ. of Washington (Faculty)
2. 1984		Daniel Rosenthal	Robust Control of Four-Disk	Rasna Corp.
3. 1985		Bruce Gardner	Strategy for Moving-Target Catch	Aerospace Corp
4. 1985		Eric Schmitz	Flex-Arm End-Point-Optimal Control	Martin Marietta (Space Robots)
5. 1985		James Maples	Flex-Arm End-Point-Force Control	Adept Robot Company
6. 1986		Wen-Wei Chiang	Quick Wrist on Flex Arm	IBM (Fast Disk Drives for computers)
7. 1986		Michael Sidman	Adaptive Control of Hi-Q Mech. System	D E C.
8. 1988		Daniel Rovner	Adaptive Control of Flexible Manip.	Orbital Sciences, Inc. Led flight control for Pegasus (Ist launch 1990)
9. 1988	*N*	Harold Alexander	ACV Space Robot Simulator	Orbital Sciences, Inc. (MIT Faculty four years)
10. 1988		Michael Hollars	Control of Flexible-Drive 2-Link Manip.	Rasna Corp.
11. 1989		Ray Kraft	End-Point Control of Flexible Robot with Mini-Manipulator	Boeing
12. 1989	*N*	Stanley Schneider	Experiments in Dynamic and Strategic Control of Coop. Manips.	Real-Time Innovations (He Started this software co.)
13. 1990		Chris Uhlik	Adaptive Control of Flex-Drive 2-Link	ArrayComm (Toyota 2 yrs)
14. 1990	*N*	Warren Jasper	Experiments in Thrusterless Robot Locomotion Control for Space Apps.	N.C. State Univ. (Faculty)
15. 1990		Brian Andersen	Experiments in End-Point Position and Force Control of a Minimanipulator	Naval Ocean Systems Center (on Point Loma)
16. 1990	*N*	Ross Koningstein	Experiments in Cooperative-arm Object Manipulation with Free-Flying Robot	SPAR Consultant (SPAR makes Shuttle robot arm)
17. 1990	*N*	Roberto Zanutta	Experiments in Adaptive Control of Cooperating Manipulators	Trimble Navigation
18. 1991	*N*	Celia Oakley	Experiments in Modeling & End-Point Control of Two-Link Flex. Manipulators	Lectus Inc.
19. 1991		Roberto Vasquez	Experiments in Two-Cooperating-Arm Manip. Fm a Platform w/Unknown Motion	Hughes Space Program Manager
20. 1992	*N*	Marc Ullman (Cellist)	Exper. In Autonomous Nav. And Control of Two-Armed, Free-Flying Space Robot	MathWorks Chief Scientist
21. 1992	*N*	Vincent Chen	Exper. In Nonlinear Adaptive Control of Multi-Manipulator, Free-Flying Space Robots	Real-Time Innovations (see above)
22. 1993	*N*	Larry Alder	Control of Flexible-Link Robotic Arm Manip. an Unknown Dynamic Payload	ArrayCom

Table I (continued)

Year		Graduate	Project in Lab (Thesis Abstract in Part II)	Subsequent Professional Path
23. 1993	*N*	Bill Dickson	Exper. in Cooperative Manipulation of Objects by Free-Flying Robot Teams	Lockheed (pointing flexible spacecraft)
24. 1993		Larry Pfeffer	Design & Control of Two-Armed, Cooperating, Flexible-Drivetrain Robot System	NIST
25. 1993		Bill Ballhaus	Exper. in High-Performance Control of Multi-Link Flex. Manip. with a Mini-Manipulator	Hughes Space Program Manager
26. 1994	*N*	David Meer	Experiments in Cooperative Manipulation of Flexible Objects	Sarcos Research Corp.
27. 1995	*N*	Ed Wilson	Experiments in Neural Network Control of a Free-Flying Space Robot	Intellization
28. 1995	*N*	Richard Marks	Experiments in Navigation of Underwater Robots using Vision Sensing	Autodesk
29. 1995	*N*	Tim McLain	Modeling of Underwater Manipulator Hydrodynamics with Application to the Coordinated Control of an Arm/Vehicle System	Brigham Young Univ. (Faculty)
30. 1995		Gerardo Pardo-Castellote	Experiments in the Integration and Control of an Intelligent Manufacturing Workcell	Real-Time Innovations
31. 1995		Andrew Conway	Autonomous Control of an Unstable Model Helicopter Using Carrier-Phase GPS Only	Silicon Genetics
32. 1995	*N*	Jeffrey S. Russakow	Experiments in Manipulation and Assembly by Two-Arm, Free-Flying Space Robots	McKinsey & Co.
33. 1996	*N*	Kurt Zimmerman	First demo of Precision Pseudolite Control of Space Robot	IntegriNautics (GPS for FAA)
34. 1996		Howard Wang	First Task-level Controlled Autonomous Underwater Vehicle	Real-Time Innovations LPS@KSC
35. 1997	*N*	Eric Miles	A Real-Time Human-Perception Interface for Task-Level Control of a Robot in Unfamiliar Environments	Seagull Technology Inc. (Human/a.c. interface)
36. 1997	*N*	H.D. Stevens	Manipulation of a Free-Floating Object using a Macro/Mini-Manipulator with Structural Flexibility	Space Systems-Loral Program Manager
37. 1997		David Miles	Real-Time Dynamic Trajectory Optimization with Application to Free-Flying Space Robots	Crystal Dynamics
38. 2000		Stephen Fleischer	Bounded-Error Vision-Based Navigation of Autonomous Underwater Vehicles	

MORE!

⇒

An ARL Brainstorming Retreat

End of TABLE I (page 3 of 3)

Year	Graduate	Project in Lab (Thesis Abstract in Part II)	Subsequent Professional Path
39. 2000	Tobe Corazzini	Onboard Pseudolite Augmentation for Spacecraft Formation Flying	Real-Time Innovations
		Have Defended Thesis	
40. 2000	Kortney Leabourne	Model Development and Coordinated Control for Underwater Manipulation	
41. 2000	Robert Kindel	Motion Planning for Free-Flying Robots in Dynamic and Uncertain Environments	Real-Time Innovations
42. 2000	*N* Heidi Schubert	Impedance Control of Flexible Macro/Mini Manipulators	
43. 2000	*N* Andrew Robertson	Spacecraft Formation Flying: Theory and Experiment	
44. 2000	*N* Bruce Woodley	Model-Free Subspace-Based H_∞ Control	
45. 2000	*N* Stefaan Sonck	Semantics of Software Components for Robot Manipulation	Real-Time Innovations
46. 2000	*N* Gordon Hunt	Multiple-Criteria Motion Optimization for Redundant Robots	Real-Time Innovations

Current PhD Students

Current Student	University as Undergraduate	Department of B.S.
47. Andreas Huster	Simon Fraser U., Br. Columbia	Electrical Engineering
48. Henry Jones	U. of Mississippi	Aerospace
49. Eric Prigge	Purdue University	Aero/Astro
50. Eric Frew	Cornell University	Mechanical Engineering
51. Edward LeMaster	U. of Washington	Aero/Astro
52. Melvin Ni	U. Ill. at Urbana-Champaign	Aero/Astro
53. Jorge Moraleda	U. of Seville, Spain	Electrical Engineering
54. Jeff Ota	Stanford University	Engineering
55. Jason Rife	Cornell University	Mechanical & Aerospace Engineering
56. Chad Partridge	U. Ill. At Urbana-Champaign	Electrical & Computer Engineering (M.S.)
57. Christopher Clark	U. of Toronto, Ontario	Mechanical & Industrial Engineering (M.S.)
58. Timothy Bretl	Swarthmore College	Engineering

TABLE II

METRICS ACHIEVED BY ARL's Ph.D. STUDENTS

TABLE III

SOME POTENTIAL METRICS FOR NASA OPERATIONAL MISSIONS

TABLE II

METRICS ACHIEVED BY ARL'S PhD STUDENTS

The selected metrics given here represent the performance achieved in this program.

Each metric target was generated by the task on which a PhD project was focused. Every result is an experimental demonstration that had never been done before anywhere. The metrics given in Table II are those measured in the laboratory or field. For each author, the data are referred to in the Abstract in Part II of this report and in the author's publications, and of course are given in complete detail in the dissertation.

Table III, which follows this one, indicates – with quantified improvement estimates – the ways that Operational Missions might well benefit from the new capability made possible by each new concept demonstrated, quantitatively, here in Table II.

a **Object-based Task-Level Control (OBTLC)** of fully-integrated two-cooperating-arm robots, both fixed (**a**) and free-flying (**b**): 18 PhD projects; first was Schneider [12].

- Among those tasks also doable by teleoperation: OBTLC yields typically 90% reduction in human workload (task is now executed unattended).

  Plus: A large new category of tasks are now possible by OBTLC that could <u>not</u> be done at all previously (and were not). We begin with *FIGURE 5:*

- Capture and slew of a free-flying target by a fixed-base two-arm robot,
  Success rate: 100%
  - Object-position peak tracking error during 25 cm/sec slew: 4 cm (= 16%)
  - Object position error in steady hold: 3mm with optics
    2cm with GPS (see **d** below)

  (Done robustly: intentional four-fold error in assumed mass of slewed object.)

- Capture of free-flying, spinning object, and gentle insertion into a receptacle:
  100% success rate; 3mm accuracy required; 40 seconds to complete.
  Prescribed-force error during gentle contact:
  steady state 0.1 n/2.5n = 4%
  Transient error: negligible after 0.2 sec time lag

- Regulation of two-arm end points despite base vibration:
  2.8mm/20mm = 15%
  (Computed torque control; no sensing of base motion) [Vasquez 19]

- Adaptive Control: Typical-trajectory tracking error (no base motion):
  1mm/1cm = 10 x improvement [Zanutta 17]

- Maintenance of commanded deformation of flexible object during assembly:
  Transient error: 0.2cm/3cm = 8%
  Steady state error: negligible [Meer 26]

System-Software Development Tools: ControlShell, NDDS, High-level software-module exchange system, all at ARL [Schneider 12, Pardo-Castellote 30, Sonck 45], plus other tools developed at RTI with ARL as a generation-bed.

- Threefold reduction in time for developing new-system software. Now in use in about 50 major places nation-wide; see Launch Processing System at end of Table III. (Used in almost every first-of-a-kind complex system development in ARL.)

b Real-Time OBTLC for two-armed free-flying robot

- Robot pushing off from one base and catching itself at another, 3.7 m away *without thrusters at all*: Terminal lateral position error 7 cm = 16% [Jasper 14]

- Two-link arm operating from free-to-move gas-bearing-supported base:
  Tracking error 0.2cm/20cm = 1% [Alexander 9]

- **Moving-target Catch,** by cooperating pair of two-link arms on free-flying base, of target traveling at 15 cm/sec and rotating @ 2 rad/sec, from a start one meter away: Time to catch: 20 sec;
  end-point accuracy: 3mm.
  Then delivered to distant place and oriented as directed, all as one single commanded task. (First completed in about 1988.) [Ullman 20].

- **Real-Time Motion Planning On the Run** for two-armed free-flying robot capturing a free-flying target among fixed obstacles:
  50% reduction in total time to execute commanded task (catch and return moving target). 99% reduction in time before robot starts moving.
  [D. Miles 37]

• First time ever (f.t.e.) autonomous capture of target that makes course change
• " " " " " " " among moving obstacles.
• Amid 5 to 10 moving obstacles: <0.5 sec preplan time; 0.25sec plan under way
[Kindel 41]

• **Human Vision as Real-Time GUI Input** to OBTLC Computer
75% reduction in time to respond to unexpected objects (estimate)
75% reduction in human work load in responding.
Often achieves task not otherwise possible.
Often avoids collisions that would otherwise occur. [E. Miles 35]

c **GPS (Only!) Control of Totally Autonomous Helicopter**
One receiver, with four antennae (plus computer). A ground receiver in the neighborhood provides for a differential system; and integer preset gets to the level of a small fraction of the 19cm wave length. Result: one to two cm sensing
• accuracy. Accuracy achieved by total flight system: about 4 cm in xy, 12 in z.
Dynamic response; In translation: period of 10 sec, damping 0.3
In rotation (vertical axis): time constant 2 sec.
[Conway 31]

• **Autonomous Helicopter tracking moving ground target,** using GPS plus on-board camera system. Accuracy 10 cm
[Frew 50; Jones 48]

d • **Local-pseudolite GPS (only) control of free-flying space robot (2D), with capture of free-flying target.**

Navigation accuracy	2 cm
Attitude accuracy	3 deg
Keeping station on a moving GPS-equipped target	4cm, 8 deg

[Zimmerman 33 completed in '96]

d • **Formation flying (station and attitude) of 3 free-flying space robots (2D) using self-calibrating GPS only, as Interferometric Astronomy model:**

Relative-location accuracy: 1 cm
Relative-attitude accuracy: 2 deg

• **using also on-board laser beam alignment:**

Relative location: 1 mm
Relative attitude: 0.01 deg
[Corazzini 39, Robertson 43]

e • **Mars Rover Self-calibrating deployed GPS (pseudolite system)**

Preliminary instrument accuracy: 5 cm
[LeMaster 51]

h • **Large Two-Link RMS with flexible drive, carrying at its end a fully-integrated pair of quick two-link arms.**

End-point position accuracy < 1cm.
10x better -- and much quicker -- than for large arm alone.
Force control of 1n +/- 0.1n
Total time for free-flying-object capture -- slew large arm; catch with mini: 4 sec.
[Schubert 42]

i • **Real-Time Mosaicing of the Ocean Floor**

Time to complete 10x20 mosaic of an area. Previous time: 2.5 hours
With new ARL system: 2.5 minutes
(Ocean scientists are very happy with 60:1 metric.)

• Drift-free operational station-keeping above ocean floor: 10 cm

This is a hugh help to pilot team during science operations: the work load is down 95%.

[Marks 28; Fleischer 38]

- **Control of the end point of a two-link arm carried by an underwater vehicle:** By controlling both arm and vehicle, using both feedback and feedforward control (and by knowing much more about the hydrodynamics of such a system than was ever known before) the end point has been held fixed to about 1cm. [McLain 29; Leaborne 40]

j Neural Network Control of Free-Flying Robot

Note: this is just a representative example of the adaptive control research that infused every project area in ARL, as noted in Section **j** of this report.

- The system was tested by giving it tasks described in section **b** above, to do; but with major, ungiven, changes in the vehicle's dynamics. In particular, some of the thrusters were plugged, and some were even turned backward. After a quite short, structured trial-and-error process, the control system had learned how to use whatever thruster configuration it actually had, to control the spacecraft quite well.

  [Wilson 27]

TABLE III

SOME POTENTIAL METRICS FOR NASA OPERATIONAL MISSIONS

To which ARL's Achievements **a** through **j** may contribute, as noted.

b Free-Flying Robot for Routine Tasks to replace a portion of Human EVA Time.

Using cm-level GPS + INS + stereo vision and tracking
(Last three are each straightforward):

- Do selected routine maintenance under OBTLC: 20% reduction in total EVA time ??
- Fetch small objects under OBTLC: accuracy 10 cm
  (with human-vision inputs)
- Interact with free satellite: rendezvous accuracy 10 cm
- Work with RMS: Capture, orient, present objects 2cm, 4 deg.
- Team with other robots for routine parts of Space Station Assy.
  (Saving in EVA time: hard to estimate)
- Astronaut Assistant under OBTLC (replace one astronaut)

d Interferometric Astronomy: Self-calibrating GPS + Laser
(Baseline of order 1 kilometer.)

- Provide highly-precise base for astronomy optics: 1 mm
  0.1 deg

  (This is where the astronomical telescopes can now begin; and then go down 7 more orders of magnitude.)

d Task-Level Control of AIRcam's Eyes

This system uses a GPS/local-pseudolite system (a la Section **d** of Table II) that is integrated with rigid-mounted camera system's output.
Operationally, INS and Vision tracking will also be essential -- and straightforward.

- **OBTLC will enable typically a 95% reduction in operator work load** [vs. the very heavy operator work load required without OBTLC] This is true for all sub tasks in the AERcam repertoire. In addition, for each sub task there are specific metric improvements, as follows:

- (i) Keep Station at a designated location
  30 cm cube, nondrifting, unattended (est.)
  [vs. estimated 200 cm cube -- but only if operator works very hard]

- (ii) Point vehicle/camera: **6^o nondrifting, unattended**
  [vs. estimated 2^o with heavy operator work load]

- (iii) Keep Station on moving astronaut (say, 1 meter/second)
  30 cm cube, nondrifting, unattended
  [vs. estimated 200 cm cube, with heavy operator work load]

- (iv) Inspect designated area of space shuttle surface (e.g., tile area)
  images located to 4 cm in GPS coordinates in real time plus permanent photo-set record in same coordinates
  [us what human can infer -- with intense attention -- from "landmarks." But nothing is better than personal human inspection.]

- (v) Future: Real-time mosiacking integrated into GPS nav system
  unattended real-time 4 cm station keeping, or navigating relative to permanent mosaic data-sets for spacecraft areas
  [vs. heavy operator work load with varying accuracy and intense attention]

e Planetary Rover

For increased science productivity through much more efficient navigation management:

- Establish Mars-Fixed Coordinates via locally deployed GPS (using self calibration) 5 cm
- Integrate Vision/Real-Time Mosaic into GPS coordinates 5 cm
- Real-time human perception GUI to update terrain/object model 2 to 4 cm

h OBTLC-managed RMS with Two-arm Surrogate Human

Move end points with speed and precision -- with respect to local points on space station, <u>or</u> to free-flying vehicle to be worked with.

- Est. 80% reduction in operator work load.
- Two-arm capture of object having unknown dynamics (e.g., fuel on board, or solar panels). Only humans in EVA can do now.
- Maintenance on a captured satellite. Est. 20% reduction in EVA time.

i OBTLC of Operational Free-Swimming Robot

- Station Keeping, with respect to bottom or wall or a floating object, either in Earth's oceans or in Europa's. For total system: 10 cm.

a Launch Processing System at Kennedy Space Center

Under development for KSC by RTI, 1998 - present, using software tools developed in ARL, see Section **a**.

Result, for the KSC project:

- Time to develop software for each subsystem: est. down by 3 x
- Reusability effect on cost: est. down by 2 x
- System structure and flexibility effect on life and maint. cost est. down by 4 x

PART II

ABSTRACT OF EVERY PhD THESIS

followed by

OTHER PUBLICATIONS OF THE AUTHORS

GORDON HUNT

No. 46

Multiple-Criteria Motion Optimization for Redundant Robots

It is an established fact that kinematically redundant manipulators, a robotic system which has more degrees-of-freedom in its joints than required to do the current task, offer greater versatility and dexterity than conventional robot manipulators. The flexible nature of redundant robotic systems makes them ideal for many applications where the environment is restrictive or dynamic. They can reach into or behind obstacles, and adjust their pose to maintain performance with out interrupting the task. The difficulty that occurs with redundancy is in specifying and controlling the extra motion inherent to redundant robotic systems, while satisfying both task and null-space requirements.

Kinematic approaches for resolving redundancy and that can be categorized as local or global optimization problems. The additional constraints needed have traditionally been joint-limit avoidance, joint-torque minimization, obstacle avoidance, improving dexterity, and singularity management. The redundancy allows these constraints to be satisfied, while at the same time performing the required task. However, in any of the traditional problem formulation methods, these additional constraints can only affect motion of the robot in the null-space. The task of the robot remains unaffected by the additional constraints. However, there are many cases (e.g., obstacle avoidance and motor saturation) where the additional objectives should also be able to directly influence the task.

In this thesis, a new method for blending the conflicting multiple objectives in the task-space and the null-space is developed. This allows a graceful and natural degradation of the task-space performance in order to satisfy the additional objectives that have been specified. A method to set priorities of the various tasks that the robot has been asked to perform will be presented. An integrated on-line algorithm, which continuously optimizes system performance based on the prioritized list of objectives, will be described. Finally, experimental results that demonstrate the effectiveness of this approach are presented.

Principal Adviser Stephen M. Rock

STEFAAN SONCK

No. 45

Robotics is a fundamentally interdisciplinary field: to build robots that interact non-trivially with their environment, it is necessary to combine modern techniques for sensing, control and decision making. Although continuous progress is being made in these individual fields, it remains strangely difficult to build a machine that combines them. Symptoms are the enormous complexity of such an integrated system and the inability to structure and control the integration process. This problem cannot be solved by applying more engineering resources to a possibly lengthy but otherwise straightforward implementation, but requires a whole new set of techniques. These techniques are software development methodologies and tools.

An attractive approach is the deployment of reusable software components that are plugged together in a domain-specific architecture and implemented in an object-oriented framework. One of the big problems with this approach is that these architectures and components often lack a clear description of their semantics: what does it mean to plug components together? what does the software component exactly do and under what conditions can it be used? This dissertation tries to understand what the semantics of such software components are and proposes a way to describe these semantics formally so that violations in the use of components can be caught early on and so that components can adjust their implementation to the way they are used in the design.

I will do this in the context of a specific architecture that is very appropriate for robotics: the monotonic signalflow architecture, in which the components are functional blocks that interact through signals. I will define a formal language, called the Requirement/Assertion Description Logic, that allows a component-designer to capture the semantics of these components at a domain-appropriate level. The semantics I am concerned with have, for example, to do with conventions of units, reference frames or mathematical properties of matrices and vectors, which are common sources of confusion and errors in software for robotic manipulation.
Using these semantics means that, while plugging together components, the designer builds a rich database of information about the design; information that, in current practice, is only available informally in documentation or in the head of the designer or -worse still- never considered. Because of the large size of this semantic database, an automatic reasoning tool is needed that combines the information about the functionality of the components (expressed in RADL) with the topology of the components (how are they connected) and generates the information in this database. This information is then used to alert the designer if there is a problem and
the individual components to reconfigure themselves. To illustrate and verify this concept, I developed a prototype tool around RADLER, the RADL Experimental Reasoner, which tries to find a good balance between fast and complete reasoning. This will show that these kind of techniques can

Principal Adviser Stephen M. Rock **Ref. 1169**

BRUCE WOODLEY

No. 44

Model-Free Subspace-Based H_∞ Control

Plant knowledge is essential to the development of feedback control laws for dynamic systems. In cases where the plant is difficult or expensive to model from first principles, experimental data are often used to obtain plant knowledge. There are two major approaches for control design incorporating experimental data: model identification/model-based control design, and model-free (direct) control design. This work addresses the direct control design problem.

The general model-free control design problem requires the engineer to collect experimental data, choose a performance objective, and choose a noise and/or uncertainty model. With these design choices, it is then possible to calculate a control law that optimizes expected future performance. Recently, there has been significant interest in developing a direct control design methodology that explicitly accounts for the uncertainty present in the experimental data. Ideally, the direct control design technique should be amenable to adaptive implementation.

This research exploits subspace prediction methods in order to develop a novel direct control design technique which permits the inclusion of plant uncertainty. The control design technique is known as model-free subspace-based H_∞ control. Two important limits are considered: as the design parameter $\Gamma \Rightarrow \infty$, the controller converges to the model-free subspace-based LQG controller. If the plant is LTI, and the amount of experimental data becomes very large, the controller is identical to a full-information finite-horizon H_∞ controller operating on the plant state estimate produced by a Kalman filter.

A computationally efficient method of updating the controller is derived, thereby enabling on line adaptation. This method is particularly effective because the computational effort required to incorporate new data is invariant with respect to the total amount of previously collected data. Furthermore, the data storage requirement does not grow as new data are collected. This method is also applicable to the model-free subspace-based LQG control design technique.

The H_∞ design technique is demonstrated through experiments utilizing the ``three disk system" - a classic flexible structure control problem. The engineer merely collects experimental data, defines a cost function, and runs the design algorithm, which returns a measure of expected performance, and the optimal controller. Exceptional control is demonstrated for the non-collocated control problem, utilizing a very short data set. In simulation, the adaptive technique is found to rapidly develop an excellent control law after just a few seconds of data collection. With little experimental data, the adaptive controller rapidly converges to the optimal H_∞ controller.

Principal Adviser Jonathan How

Refs. 1137, 1161, 1162, 1165, 1177, 1178, 1184, 1187

ANDREW ROBERTSON

No. 43

Spacecraft Formation Flying: Theory and Experiment

Spacecraft formation flying is an enabling technology for many future space science missions such as separated spacecraft interferometers (SSI). However the sensing, control and coordination of such instruments pose many design challenges. SSI missions will require precise relative sensing and control, fuel-efficient, fuel-balanced behavior to maximize mission life and group-level autonomy to reduce operations costs. Addressing these requirements requires precise relative sensing and estimation, enhanced control capabilities such as cooperative control (multiple independent spacecraft acting together), and group-level formation management. In addition, an informed control system architecture design is required to manage distributed sensing and control system resources.

This talk presents research that defines an end-to-end control system, including the key elements unique to the formation flying problem: cooperative control, relative sensing, coordination, and the control system architecture. The control system design optimizes performance under typical spacecraft constraints (e.g. on-off actuators, finite fuel, limited computational power, limited contact with ground control, etc.) Standard control techniques have been extended, and new ones synthesized to meet these goals. In designing this control system, contributions have been made to the field of spacecraft formation flying control including: an analytic two-vehicle fuel-time optimal cooperative control algorithm, a fast numeric multi-vehicle, optimal cooperative control algorithm that can be used as a feedforward or feedback controller, a fleet-level coordinator for autonomous fuel-balancing, validation of GPS-based relative sensing for formation flying, and trade studies of distributed approaches to the relative control and estimation problems. The lessons learned from this research have been validated in simulation and experiment.

Principal Adviser Jonathan How **Ref. 1163, 1166, 1176, 1186, 1188**

HEIDI SCHUBERT

No. 42

Impedance Control of Flexible Macro/Mini Manipulators

Construction and maintenance of on-orbit crew-operated hardware is currently done mostly by extra-vehicular astronauts. Use of robotics for some of these tasks provides the opportunity for both increased safety for the astronauts and major ground-crew cost savings.

An effective space robotic manipulator must be lightweight, have a large workspace, and be capable of fine dexterous control. A large lightweight manipulator will necessarily be quite flexible, limiting the achievable end-point bandwidth. One way to still achieve all of these objectives is via advanced, astute control of a macro/mini manipulator: a large lightweight manipulator carrying a small dexterous manipulator, such as is planned for the International Space Station.

The goal of this work is therefore to control a flexible-joint macro carrying a two-cooperating-arm mini manipulator. For ease of use, a low-level controller should be designed such that the user or automated planner need only command the desired end-point motions and forces. Designing an end-point controller for a macro/mini manipulator presents many opportunities and challenges. Such a manipulator system is highly non-linear, has low frequency flexibility, has dynamic coupling between the macro and mini, and has valuable redundant degrees of freedom.

A smart method for controlling manipulators is impedance control, which specifies a desired force-velocity relationship at the end-point of the manipulator system. Both end-point position and force are controlled, enabling smooth contact with the environment. Using operational space control, the dynamics of the manipulator are transformed into operational or end-point coordinates for implementation of the impedance law. The operational space method also enables a secondary control of the redundant degrees of freedom, without degrading the primary end-point impedance task. This thesis presents new theoretical advances that enable extending the concepts of operational space and impedance control to redundant joint-flexible robots. Important advances include a new method for choosing the end-point impedance and null-space controller that performs much better.

The new control concepts are verified on an experimental macro/mini manipulator. The experimental system is planar with a two-link flexible macro carrying a two-cooperating-arm mini. The control law is used to semi-autonomously perform a variety of tasks: capture and manipulate a free-flying object; capture, manipulate, and insert a flexible object; and accelerate a large object with a prescribed force.

Principal Adviser Jonathan How **Ref. 1170**

ROBERT KINDEL

No. 41

Motion Planning for Free-Flying Robots in Dynamic and Uncertain Environments

With the successful flight of Aercam Sprint in late 1997, and the imminent launch of the Mobile Servicing System for the International Space Station, the idea of space robotics is advancing quickly from the realm of science fiction to reality. While these early robots have been technology demonstrators, the eventual goal of space robots is to perform assembly, maintenance and inspection tasks either in cooperation with or in lieu of astronauts. Current space robots utilize a teleoperation mode of control, where one or more operators commands the robot at an extremely low level. This inefficiently assigns the astronaut the difficult task of controlling a complex
robot, and limits the number and complexity of the robots in operation. These difficulties can be alleviated through the automation of low-level robot tasks so that the user inputs directions such as "Place the solar panel here". This methodology is called Object Based Task-Level Control and has been used successfully to combine the efficiency of automatic control with the task planning capabilities of human operators.

A critical capability required to increase the autonomy of free-flying robots is the automatic generation of collision-free trajectories. This especially difficult for free-flying robots for a number of
reasons: a) the stringent dynamic constraints (low robot acceleration) intrinsic to such vehicles, b) the possibility of moving obstacles in the workspace, c) a desire to have a complete plan formed before beginning a motion (to allow oversight), and d) the requirement for very fast planning. Additionally, robustness to sensor and modeling errors is desirable. While previous efforts have satisfied one or two of these requirements, this work presents a motion planning system
that provides all these capabilities. The planning algorithm is based on a randomized path planning technique, which searches the workspace for a path by growing a directed tree of nodes in the (state, time) space by integrating random controls until a node is found to be within the Goal Region. This planner achieves dynamically constrained motion plans in less than .25 seconds for most workspaces even in the presence of many (5-10) moving obstacles. Such efficient path computation enabled the development of a replanning system which generates new paths when obstacles do not behave as predicted at planning time. The resulting motion planning system enables task-level control of a free-flying space robot with real-time
response to user commands and to changes in its environment. It was tested for planar workspaces both in simulation and on the Free-Flying Robot test bed. The planner was also tested in simulation in 3D (translation only) environments to demonstrate its extensibility to the space robot mission.

Principal Adviser Stephen M. Rock **Ref. 1190, 1191**

KORTNEY LEABOURNE

No. 40

Model Development and Coordinated Control for Underwater Manipulation

Robots for underwater exploration have become a key technology for the field of marine science. Tasks that involve intervention with the environment, such as sample collection, tool operation, or instrument deployment, require the use of manipulators. Certain underwater operations have necessitated the development of small robots with automated low-level controls. New research is being done on adding manipulators to these autonomous vehicles to enable the performance of intervention tasks. The problem that arises for these arm-vehicle systems is that there can be significant dynamic coupling between the arm and the vehicle, causing the vehicle to ``swim" whenever the manipulator is actuated. This affects the ability of an autonomous system to achieve precise end point placement for intervention tasks, as well as the control performance of the system as a whole.

Two issues that are affected by this complex interaction have been addressed in this research. First, a good model of the manipulator hydrodynamics is necessary for use in planning and control algorithms for the system. The dominant forces of the coupling are the drag forces and torques due to motion of the manipulator. Experimentation has shown that the existing models in the literature do not adequately predict these terms. This presentation will show a new model for the drag forces on a two degree-of-freedom underwater manipulator that more accurately represents the surrounding flow field. This model was used successfully in predicting joint torques for a fixed-base manipulator, as well as in a control scheme for hovering the OTTER experimental underwater vehicle during manipulation maneuvers. Second, coordinating arm-vehicle motions in an efficient manner is important for autonomous systems in order to achieve the desired performance measure, such as minimizing energy consumption or reducing vehicle motion in a certain direction during a manipulation task. Current work on motion planning for underwater systems is limited to reactive planning for constrained end-effector paths. This work presents a new version of an analytic tool called a Coupling Map for underwater arm-vehicle systems that can be applied to a different range of coordination problem formulations. This tool provides a graphical representation of the complex coupling characteristics of these systems and can be used to plan arm joint trajectories that regulate the vehicle's response. Arm motions planned to minimize vehicle motion were demonstrated on the OTTER arm-vehicle system with significant improvements.

Principal Adviser Stephen M. Rock **Refs. 1168, 1181**

TOBE CORAZZINI

No. 39

Formation flying of multiple spacecraft is an enabling technology for many future space missions. By separating a monolithic structure into several spacecraft that collectively *act* as a single structure, virtual spacecraft of unlimited size can be flown. This will enable new scientific missions, based on distributed yet coordinated measurements. Examples include stellar interferometry missions and gravity field mapping.

One of the fundamental requirements of formation flying is precise knowledge of the relative position and attitude between the vehicles. The Global Positioning System (GPS) has been shown to be an accurate position and attitude sensor both on earth and in space. The use of GPS in space is limited to orbits with adequate visibility to the NAVSTAR GPS constellation, typically LEO. For higher elevation orbits, such as MEO, GEO, and highly elliptical orbits, visibility of the GPS constellation can easily fall to two or even zero satellites. In such conditions, insufficient measurements are available for a formation of vehicles to solve for all relative position and attitude states. However, by augmenting the available NAVSTAR satellite signals with GPS pseudolites placed onboard the vehicles in the formation, sufficient signals are available to solve for relative position and attitude between all vehicles. The onboard pseudolite system can even operate during times of total occlusion of the satellites. Thus, an onboard pseudolite system can be used in environments where the NAVSTAR satellites are known to be totally unavailable, such as deep space.

This dissertation presents the development of a relative positioning sensor for a fleet of vehicles, combining information from onboard pseudolites with information from the GPS satellites. Relative positioning is conducted on a fleet of three prototype spacecraft, in a laboratory environment as proof of concept. System robustness is improved through a novel carrier phase reinitialization approach.

Principal Adviser Jonathan How **Refs. 1166, 1176, 1179**

STEPHEN FLEISCHER

No. 38

Bounded-Error Vision-Based Navigation of Autonomous Underwater Vehicles

Underwater vehicles are being used extensively to explore the ocean depths, but to enhance their utility for marine scientists and other end-users, new navigation capabilities must be developed. Vision-based mosaicking is a promising new technology with several inherent benefits: it is inexpensive, utilizes any existing camera on-board the vehicle, and does not require extensive set-up or calibration. Other alternatives for navigation exist, but have limitations in the underwater environment: GPS cannot penetrate the ocean surface; acoustic positioning systems require a transponder net to be constructed before a particular area can be explored; and sonar systems are often bulky and exhibit poor accuracy, depending on the cost of the system.

While the capabilities of video mosaicking and dead-reckoning navigation have been demonstrated in previous research, this work is fundamentally limited in its achievable accuracy. Since the vehicle global position estimates are determined through dead reckoning, the error variance increases according to a random walk based on the vehicle path length. This unbounded error propagation makes attempts at long-term navigation inaccurate and unreliable.

The purpose of this thesis is to improve the accuracy of these mosaics, thereby enhancing vehicle position estimation for navigation. Since the alignment of images within a mosaic is still susceptible to dead- reckoning errors, crossover points (where the vehicle path loops back upon itself) are used to provide additional vehicle position/image alignment information. By correlating two overlapping images at each crossover point, a corroborating measurement of the vehicle's current global position is obtained, which can be used to reset the dead-reckoning integration error, thereby improving future position estimates. To improve past position estimates (which affect image alignment within the mosaic), the new position estimate is propagated backwards around the loop in the vehicle path using sensor model equations. This reduces position errors around the entire loop and improves the accuracy of the mosaic map.

Theoretical and experimental results of this work will be presented, including demonstrations on both OTTER, an autonomous underwater vehicle, and the ARL precision gantry platform, a system capable of controlling a camera head in 6 DOF within its workspace. This work has been performed under a joint effort between the Aerospace Robotics Laboratory (ARL) at Stanford University and the Monterey Bay Aquarium Research Institute (MBARI).

Principal Adviser Jonathan How

Refs. 1126, 1127, 1142, 1156, 1167, 1168, 1171, 1180, 1183

DAVID WILSON MILES

No. 37

Real-Time Dynamic Trajectory Optimization with Application to Free-Flying Space Robots

The capability of robots to complete tasks or entire missions autonomously relies heavily on their ability to plan. Good planners must not only be able to produce efficient plans but must also be able to modify those plans quickly in response to unpredicted events. Unfortunately these two goals are often conflicting ones, with only slow, complex planners able to produce efficient plans, and only quick, simple planners able to react to unpredicted events.

The research presented in this dissertation focuses on the development of a real-time dynamic trajectory optimization system that provides both high performance motion planning capabilities and the new ability to react effectively to uncertainty in the environment. This system achieves these capabilities by utilizing simultaneous planning and execution to improve the robot's trajectory while the robot is in motion along the trajectory. Although other robotic systems have used simultaneous planning and execution, this dissertation applies the concept to dynamic trajectory optimization, a sophisticated technique for computing high-performance trajectories that has previously been used only in off-line planning applications and in simulation.

The resulting system uses a non-linear optimization algorithm to continually improve an initial trajectory, subject to the dynamics of the system and constraints on the (e.g., free-flying) robot's motion in order to minimize a weighted sum of the fuel and time required to complete the trajectory.

Using this system, several motion-planning tasks are demonstrated experimentally on a thruster-propelled free-flying robot. The most complex of these tasks requires the robot to travel around a pair of stationary obstacles and intercept, in a highly efficient manner, a moving target vehicle that is maneuvering unpredictably.

Two key contributions that enabled this demonstration are: 1) A system in which the constraint equations of the dynamic trajectory optimization system are based on live sensor data from the robot. 2) A segmented planning framework that enables both efficient optimization and limited delay in reacting to unexpected events. This dissertation discusses these and other contributions that were required in order to enable a safe, efficient, and high-performance intercept capability for the free-flying robot system.

In addition, this dissertation presents a new theoretical analysis of the relative performance of real-time and on-line planning systems. The analysis uses a model of planner performance to evaluate the relative performance as a function of two non-dimensional parameters, the "optimizability" and the "planning speed". The results of the analysis show that even in a static and exactly known environment (the only situation where an on-line planner does work), a real-time planner always provides better performance than the best possible on-line planner; in fact up to 1.5 times better performance, the largest ratio occurring (in this restricted case) when the time required to find a good plan is comparable to the time required to execute that plan. This intuitive result, in addition to the method for analysis of relative performance versus "optimizability" and "planning speed", will guide those future designers who have only a static environment as to when real-time planning should be used and as to the benefits that it may provide.

Finally, this dissertation quantitatively compares the experimental performance of the real-time planner with the performance of the on-line and the reactive planners. The results show first that in a static, exactly known environment, the real-time planner provides 1.1 times better performance than the on-line planner and 1.4 times better performance than the reactive planner.

What is most important, however, is that in the much-broader robotic arena of dynamic, uncertain environments, the experimental results of this research show that while the on-line planner is unable to complete the task at all, the real-time planner can complete the task, and provides 2.4 times better performance than the reactive planner. The final experimental demonstration highlights the significant contribution of real-time dynamic trajectory optimization in providing a new high-performance motion planning capability for operating in the much broader and important arena of dynamic, uncertain environments.

Principal Adviser Stephen M. Rock **Refs. 1126, 1143, 1159**

HOMER D. STEVENS

No. 36

Manipulation of a Free-Floating Object Using a Macro/Mini-Manipulator with Structural Flexibility

A revolutionary new generation of operational robots is being developed to interact with uncertain, dynamic environments. These new robots offer many exciting capabilities such as the capture of errant satellites by the Space Shuttle Remote Manipulator System, and the removal of nuclear waste from a large temporary storage tank. These tasks illuminate many challenging robotics issues, and in particular the problem of bringing a robot into stable contact with objects that are free to move in the environment.

Interaction with a dynamic object imposes a relationship between the manipulator's position and the contact force that is well modeled as a generalized impedance. Controlling the manipulator's dynamic response to follow that of a specified impedance function complementary to the impedance of the dynamic object enables smooth interaction with that object. The specified impedance function must be matched to the environment, so that the combined manipulator-object system is well behaved, much like a matched-impedance electrical circuit. The proper specification and control of the desired complementary impedance function, called *impedance control*, provides a unified approach to both unconstrained and constrained motion in an uncertain, dynamic environment.

The benefits of impedance control have been demonstrated using "rigid" robots, that is robots where the fundamental frequency of the structural vibration modes is several orders of magnitude higher than the task bandwidth. This research extends the application of impedance control to a large, structurally flexible macro-manipulator carrying a small rigid mini-manipulator. One example of this class of robots is the Space Station Remote Manipulator System and Special Purpose Dextrous Manipulator combination currently under development.

This dissertation presents new synthesis concepts that enable impedance control to be achieved for the first time using a structurally flexible macro/mini-manipulator. These concepts include a unique methodology for partitioning the global performance objective into subsystem performance objectives, a new synthesis approach for designing the control system of a macro/mini-manipulator that exploits the inherent bandwidth separation to enable the use of the successive-loop-closure concepts, and the astute use of feedforward compensation for rapid, precise control.

The theoretical developments are experimentally demonstrated using a macro/mini-manipulator with significant structural flexibility – the frequency of the first vibration mode is 3 Hz, which is well within the frequency range of control interest. These results demonstrate fine, gentle contact with an object fixed in the environment, gentle initial contact and the firm maintenance of contact with an object completely free to move in the environment, and the prompt capture, by stopping all translation, of a freely moving object. These experiments demonstrate that impedance control enables a structurally flexible macro/mini-manipulator to achieve very precise automatic control of a free-floating object.

Principal Adviser Jonathan How **Refs. 1114, 1154, 1175**

ERIC S. MILES

No. 35

A Real-Time Human-Perception Interface for Task-Level Control of a Robot in Unfamiliar Environments

Recent advances in the development of semi-autonomous robotic systems offer numerous potential advantages in many engineering and science endeavors. Significant reductions in cost, time and risk, as well as increased capability, can be obtained by utilizing intelligent machines to assist humans. However, the use of robots also introduces many challenging issues, including the need for high-bandwidth stable control despite communication delays and operator fatigue. In response to these challenges, the Stanford Aerospace Robotics Laboratory has pioneered the Task-Level Control architecture, which enables humans to direct, from a strategic level, sophisticated tasks that a robot then executes autonomously.

The research reported here is intended to extend the Task-Level Control architecture significantly — by using human perception in a natural way — to work well in unfamiliar environments. An unfamiliar environment is defined to be one about which it is impossible to have perfect and complete knowledge before developing and deploying a robotic system. Clearly, every work environment is, to some extent, unfamiliar. This research has shown that drawing intimately, in real time, upon a human's deep visual perception is extremely effective in overcoming such unfamiliarity.

A novel interactive vision-based operator interface for directing a highly autonomous robot operating in an unfamiliar environment is presented. Intuitive interaction with a live-video display from cameras on board the robot is used in combination with stereo-vision algorithms to maintain the operator's attention at the overall object-level during the modeling process. With this interface, the human's remarkable ability to discern entire object-level constructs is utilized to produce quick, cogent and robust models of unexpected and unknown objects in the environment.

Once unfamiliar objects have been suitably modeled, tasks involving those objects can be directed via the Task-Level Control architecture. Utilizing on-board sensing, low-level dynamic-control autonomy, strategic logic, and path-planning algorithms, the Task-Level Control architecture enables an operator to request effortlessly sophisticated, object-based tasks which the robot then executes autonomously. Tasks such as robot navigation and the capture and manipulation of previously unfamiliar, moving objects in a newly-modeled, obstacle-cluttered environment have been successfully demonstrated. Experimental results with a free-flying laboratory robot are presented.

Principal Adviser Robert Cannon **Refs. 1114, 1140, 1158**

HOWARD H. WANG

No. 34

Experiments in Intervention Autonomous Underwater Vehicles

Underwater robots have the potential to enhance greatly human ability to explore and utilize the world's oceans. Currently, skilled pilots teleoperate tethered systems called ROVs (remotely-operated vehicles) to perform tasks such as video and sonar mapping, servicing and repair of instruments and structures, and biological and geological sample collection. Many research institutions are studying autonomous underwater vehicles (AUVs) in order to reduce the cost and increase the capabilities of undersea robots. However, the capabilities of current AUVs have been largely limited to survey and sample tasks with minimal interaction (e.g., manipulation) with the ocean environment.

The ability of commanding underwater robots from a high human/machine interaction-level to manipulate objects in the environment represents a significant advancement towards increasing humankind's capacity to work under the sea. Intervention tasks such as instrument servicing and underwater construction are vital to the future of ocean exploration. The work presented in this thesis establishes a new class of underwater robotic systems with intervention capabilities—the Intervention Autonomous Underwater Vehicle (IAUV). Through this research, in a joint program between the Stanford University Aerospace Robotics Laboratory (ARL) and the Monterey Bay Aquarium Research Institute (MBARI), OTTER—an *Ocean Technology Testbed for Engineering Research*, the world's first IAUV, has been developed to investigate experimentally supporting technologies that will enable this new class of underwater robots. OTTER's unique thruster configuration gives it control over all six degrees of freedom that is required for free-floating manipulation.

Although manual teleoperation is a powerful method for controlling remote robotics, human-controlled servo loops require high data-transfer rates with minimal time delays and do not utilize fully the abilities of either half of the human/machine team. In this work, the general principles of Object-Based Task-Level Control, where human perception and judgment are intelligently merged with computer computation and control, have been adopted in the design approach. In doing so, the constraints on communication between the human and robot are reduced, allowing the human to direct intervention actions from a high, *task* level through the limited bandwidth of devices such as acoustic modems. More importantly, the capabilities of the resulting human/robot team are beyond that of either manual teleoperation or total autonomy alone. These powerful capabilities can be used both in the near term by existing ROVs and in the long term by IAUVs.

The philosophy of concurrently specifying a programming architecture with software tools is introduced as a methodology for creating shareable architectures. A generic programming architecture for underwater robots is a direct contribution of this research. This architecture can be easily adopted by other robotic programmers by using an associated set of off-the-shelf software tools that have been assembled to create components fitting together in an unified framework. This tri-level architecture addresses issues at all levels of command from the human interface to actuator control. Modular components and a variety of standard libraries establish the flexibility and extensibility of the architecture to other hardware systems.

Specifically to support intervention, a practical stereo-vision sensing system was created to locate underwater objects that can be outfitted with fiducial markers. Also, an unique approach called Constrained Relative Trajectories was developed to control the robot with respect to an object without occluding the vision system. Integrated together within the OTTER IAUV, the design approach and the newly-developed technologies contributed by this thesis are validated experimentally in the first-ever demonstration of a multi-phased intervention mission—where OTTER successfully searches for, finds and approaches, docks to and retrieves an object sitting at the bottom of a test tank upon high-level command of a human supervisor.

Principal Adviser Stephen M. Rock

Refs. 1093, 1106, 1125, 1126, 1146, 1151, 1153, 1155, 1156, 1173

KURT RONALD ZIMMERMAN

No. 33

Experiments in the Use of the Global Positioning System for Space Vehicle Rendezvous

Humanity's destiny in space is intimately tied to highly automated mechanisms, and as such, the ability for humans and machines to cooperate as an integrated team will determine the success of ambitious space missions of the future.

Autonomous vehicles are only as capable as the information afforded to them by their sensors, which has led to an ever increasing need for more advanced sensors. Technologies related to the Global Positioning System (GPS) have matured to the point where they are well suited for real-time control of autonomous vehicles both in space and terrestrially. This dissertation reports research performed in the Stanford Aerospace Robotics Lab to create and demonstrate new basic knowledge and techniques for using GPS to increase the sensing capabilities of free-flying space robots, and more generally, to explore how this advanced sensor can improve the capabilities of the human-robot team in space and on earth.

A comprehensive prototype system was built and demonstrated. The system consisted of a microcosm simulation of the space environment, two prototype space vehicles, consummate software systems, and an intuitive human-robot interface. The space environment was emulated through a constellation of GPS pseudo-satellites (pseudolites) and an air-bearing support system which provided the drag-free, zero-g characteristics of space in two dimensions for the prototype space vehicles. Proof-of-concept demonstrations showed that GPS sensing alone can be sufficient to perform precise intercept and capture of a free-floating target by an autonomous free-flying space robot. Other demonstrations showed how this type of sensor could enable unprecedented capabilities in space such as performing distributed science missions using several vehicles flying in formation.

The breakthrough of Differential Carrier Phase GPS technology, combined with the novel, inexpensive local GPS pseudo-satellite transmitters, enabled the successful in-lab demonstration of GPS-based control for precise robotic navigation. Since the experiments were carried out indoors where GPS satellite signals could not be received, the constellation of six GPS pseudolite transmitters was used exclusive of the NAVSTAR GPS satellites. The indoor GPS environment created by the close-range pseudolite transmitters required development of new algorithms for resolving vehicle positions and attitudes from the carrier phase measurements.

By performing these proof-of-concept experiments, many new arenas for application of GPS sensing have been conceived, ranging from the use of pseudolites for advanced space missions to indoor sensing of mobile manufacturing robots. In addition, new methods for initializing and calibrating GPS sensors were developed, and future directions for increasing the utility of this type of sensor were identified.

Principal Adviser Robert Cannon **Refs. 1113, 1123, 1141, 1163**

JEFFREY S. RUSSAKOW

No. 32

Experiments in Manipulation and Assembly by Two-Arm, Free-Flying Space Robots

Research in advanced manipulation by robotic systems has led to interest in multi-arm/dynamic base manipulator systems – robots in which two or more manipulators extend from a common macro-manipulator or vehicle. These systems possess characteristics that are inherently beneficial to dexterous manipulation, such as redundancy, multiple arms, and macro-mini dynamic properties.

Free-flying space robots are one example where the use of multiple manipulators stemming from a single mobile vehicle offer unprecedented capability. A mobile base enables the robot to work over an unlimited workspace; multiple end-effectors enable both the execution of several tasks simultaneously and the cooperative manipulation of cumbersome objects; and redundant degrees of freedom and macro-mini dynamic properties enable the robot to achieve fast, precise manipulation at the end-effectors even though the robot body may be dominated by slower dynamic behavior.

While previous research has been conducted to control multi-arm/dynamic-base systems, an approach has never been pursued in which the redundancy of these systems has been exploited fully to focus on just the manipulative task. Past efforts have attempted to control with equal priority both the manipulative task executed at the robot hands and the control of the redundant degrees-of-freedom associated with the robot body and posture.

This thesis proposes a new, dynamically-partitioned control framework for multi-arm/dynamic-base manipulator systems, in which the performance of a robot at the manipulative task is deemed paramount. Pursuant to this goal, the entire redundant system works in concert to achieve the best possible dynamic performance at the robot end-effectors. Control of the redundant degrees of freedom of the robot are controlled using only dynamically consistent combinations of forces and torques that will not introduce undesired accelerations at the task.

The approach developed in this work offers the dual benefits of improved dynamic performance of the robot during manipulative tasks and greatly simplified programming of the robot to achieve extended, sophisticated tasks. As the control of the redundant degrees of freedom is designed so that it cannot degrade performance at the robot task, the control of the redundancy and the control of the task may be designed separately.

The novel control framework has been developed by extending the Operational Space Control Framework for single-arm and cooperating single-arm manipulators to the larger class of multi-arm/dynamic-base manipulators. Under this new Extended Operational Space Framework, redundant, multi-arm/dynamic base systems can demonstrate precise dynamic control in operational space (i.e. the space in which the task occurs).

The new Extended Operational Space Framework has been developed and experimentally validated on two-arm, free-flying space robot prototypes. These robots, which float in two-dimensions on an air-bearing and move about with the use of gas thrusters and momentum wheels, have been programmed to perform object acquisition, transport, and assembly tasks in a free-floating space environment under the new control framework.

Principal Adviser Stephen M. Rock **Refs. 1097, 1098, 1112, 1132, 1135**

ANDREW RICHARD CONWAY

No. 31

Autonomous Control of an Unstable Model Helicopter Using Carrier Phase GPS Only

This thesis contains the results of my experiments in using carrier phase Global Positioning System (GPS) techniques to totally control an inherently unstable model helicopter for the first time. In the process a new algorithm for determining the unknown integer wavelength offsets for attitude calculation was devised.

The helicopter is capable of hovering autonomously. It uses four GPS antennas on the helicopter and a ground reference station to determine position and attitude to precisions of roughly a centimetre and a degree, both at a ten Hertz update rate.

The new algorithm for integer resolution allows integers to be resolved in a computationally efficient manner with fewer satellites in view than previous algorithms, allowing use in a greater number of applications.

This thesis describes the overall problems, approaches, and philosophy of design, then contains detailed descriptions of the various logical parts of the project. A description is given of GPS, carrier phase approaches, and how position, velocity, attitude and attitude rate can be calculated, and a description of the new algorithms that make this possible. The hardware used in this project is then described, followed by the software for flight and analysis. The results of flight tests are given, and then some conclusions and suggestions for further work in this valuable arena are presented. The appendices contain comprehensive technical details of the hardware and software.

Principal Adviser Robert Cannon **Ref. 1137**

GERARDO PARDO-CASTELLOTE

No. 30

Experiments in the Integration and Control of an Intelligent Manufacturing Workcell

This thesis comprises the experimental development of an intelligent, dual-arm robotic workcell. The system combines a high-level graphical user interface, an on-line motion planner, real-time vision, and an on-line simulator to control a dual-arm robotic system from the task level.

The graphical user interface provides for high-level user direction of the task to be done. The motion planner generates complete on-line plans to carry out these directives, specifying both single and dual-armed motion and manipulation. Combined with the robot control and real-time vision, the system is capable of performing object acquisition from a moving conveyor belt as well as reacting to environmental changes on-line.

The thesis covers in detail four main topics:

1. System design and interfaces. The system is based on a novel "interface-first" design technique. This technique structures the complex command and data flow as combinations of three fundamental robotic interface components: the world-state interface, the robot-command interface, and the task-level-direction interface.

2. Network communication architecture. Complex distributed robotic systems require very complex data flow. A powerful new subscription-based, network-data-sharing system, was developed (and is being commercialized) that enables transparent connectivity.

3. Control system. The architecture and design of the hierarchical control system for the experimental dual-arm assembly workcell is described.

4. Path time-parameterization. A fast (linear-time, proximate-optimal) solution to the fundamental problem of time-parameterization of robot paths is presented.

The design was verified experimentally in a dual-arm robotic workcell. Experimental results are presented showing the system performing complex, multi-step tasks autonomously, including dual-arm object acquisitions from a moving conveyor, object motion among obstacles, re-grasps, and hand-overs. All these tasks occur under task-level human supervision.

Principal Adviser Robert Cannon

Refs. 1084, 1089, 1109, 1111, 1116, 1124, 1129, 1130, 1131, 1133, 1152, 1172, 1173

TIMOTHY W. McLAIN

No. 29

Modeling of Underwater Manipulator Hydrodynamics with Application to the Coordinated Control of an Arm/Vehicle System

For users of unmanned underwater vehicles, manipulators have become a valuable tool in performing a wide variety of tasks, from scientific sampling in the ocean to maintenance and construction of underwater structures. In some situations, the addition of manipulators to an underwater vehicle poses significant control challenges due to the hydrodynamic interactions between the arm and the vehicle: When the arm is moved while the vehicle is hovering in open water, the large hydrodynamic forces acting on the arm can cause the vehicle to "swim" away from its desired station, degrading the operator's ability to position accurately the manipulator end point.

To compensate for this dynamic coupling, the nature of the hydrodynamic forces acting on the manipulator must be well understood. This dissertation describes efforts to characterize the fundamental hydrodynamics of a single-link arm undergoing typical robotic slews. The product of this characterization is a new accurate real-time-implementable model of the hydrodynamic forces and torques acting on a circular cylinder ($length/diameter = 9.1$) swinging rapidly about one end through moderate angles (< 120 degrees) in a start-stop fashion. This model was developed through a balanced combination of theoretical development and experimentation. A two-dimensional potential-flow-theory analysis for a cylinder undergoing unsteady motions formed the starting basis for the hydrodynamic model. This analysis was extended semi-empirically to three dimensions using a strip-theory methodology. Valuable insight into the behavior of the hydrodynamic forces was gained through experimental flow visualization and direct measurement of forces at locations along the span of the cylinder. State-dependent drag and added-mass coefficients were identified from force and torque measurements using a strategy developed in this work. This research represents the first experimental investigation of the hydrodynamic forces acting on underwater manipulators.

As an example application of the new hydrodynamic model, the model was used to predict the arm/vehicle interaction forces for a system consisting of a free-swimming vehicle with a movable single-link arm. With this model of the arm/vehicle interaction forces, a coordinated arm/vehicle control strategy was developed. To demonstrate the effectiveness of this controller, experiments were conducted using the OTTER vehicle at the Monterey Bay Aquarium Research Institute (MBARI). Under this model-based approach, interaction forces acting on the vehicle due to arm motion were predicted and fed into the existing vehicle position feedback controller. Using this method, vehicle station-keeping capability was greatly enhanced: Errors at the manipulator end-point were reduced by a factor of over six when compared to results when no control was applied to the vehicle, and by a factor of 2.5 when compared to results using only position feedback for controlling the vehicle subsystem. Using the coordinated-control strategy, arm end-point settling times were reduced by a factor of three when compared to those obtained with arm and vehicle position feedback control alone. These dramatic performance improvements were obtained with only a five percent increase in the total applied thrust.

Principal Adviser Stephen M. Rock

Refs. 1090, 1126, 1144, 1145, 1150, 1157, 1164

RICHARD LEE MARKS

No. 28

Experiments in Visual Sensing for Automatic Control of an Underwater Robot

Many underwater robot tasks performed currently are observational in nature, including those for inspection and exploration applications. The information of consequence for these tasks is visual imagery; therefore, visual sensing is an ideal sensing approach since it directly measures visual information. Despite the potential benefits offered by visual sensing, several complications have kept it from being utilized to its full potential for automating the control of underwater robots. General issues that must be faced (independent of the medium) include unstructured scenery, geometric ambiguities (because images are two-dimensional projections of three-dimensional information), limited field of view, and the processing of massive amounts of image data. Additional underwater-specific difficulties include limited viewing range, low contrast, lighting variations, and marine snow.

This disseration describes efforts to develop new visual sensing technologies useful for automatic control of underwater robots. Laplacian-of-Gaussian sign-correlation, a previously-developed computer-vision technique, is established as an effective approach for determining correspondences in underwater imagery. Its robustness to low contrast, brightness and contrast variation, nonuniform lighting, and marine snow are analyzed. In addition, the basic theory of Laplacian-of-Gaussian sign-correlation is extended to predict the effects of image scaling and rotation on correlation degradation.

Image correspondences are used to compute geometric image quantities including stereo disparity, optical flow, and optical displacement; these measurements are in turn used to determine terrain-relative and object-relative robot state. Terrain-relative state is calculated by combining optical-displacement and stereo-disparity measurements with nonvisual measurements of the camera pointing-direction. Object-relative state is determined by locating an object in the scene using motion (optical flow) and range (stereo disparity) segmentation.

To demonstrate the benefit of visual sensing for underwater robot control, this research investigates the automation of three tasks: fish tracking, station keeping, and video mosaicking. In each of the tasks, visual sensing is used as the primary feedback for control. The tasks were demonstrated experimentally using *OTTER*, a semiautonomous underwater robot designed specifically for automatic control research. In addition, automatic video mosaicking of the ocean floor was performed using the Monterey Bay Aquarium Research Institute's *Ventana* vehicle. The results of these experimental demonstrations conclusively establish that visual sensing can be used effectively for automatic underwater-robot control.

Principal Adviser Stephen M. Rock

Refs. 1093, 1106, 1107, 1115, 1118, 1122, 1125, 1126, 1136, 1142

EDWARD WILSON

No. 27

Experiments in Neural-Network Control of a Free-Flying Space Robot

Because of their capabilities for adaptation, nonlinear function approximation, and parallel hardware implementation, neural networks have proven to be well-suited for some important control applications.

However, several important issues are present in many real-world neural-network control applications that have not yet been addressed effectively in the literature. Four of these important generic issues are identified and addressed in some depth in this thesis as part of the development of an adaptive neural-network-based control system for an experimental free-flying space robot prototype.

The first issue concerns the importance of true system-level design of the control system. A new hybrid strategy is developed here, in depth, for the beneficial integration of neural networks into the total control system. The basic philosophy is to borrow heavily from conventional control theory, and use the neural network as a key subsystem just where its nonlinear, adaptive, and parallel processing benefits outweigh the associated costs.

A second important issue in neural network control concerns incorporating *a priori* knowledge into the neural network. In many applications, it is possible to get a reasonably-accurate controller using conventional means. If this prior information is used purposefully to provide a starting point for the optimizing capabilities of the neural network, it can provide much faster initial learning. In a step towards addressing this issue, a new generic "Fully-Connected Architecture" (FCA) is developed for use with backpropagation. This FCA has functionality beyond that of a layered network, and these capabilities are shown to be particularly beneficial for control tasks. For example, they provide the new ability to pre-program the neural network directly with a linear approximate controller.

A third issue is that neural networks are commonly trained using a gradient-based optimization method such as backpropagation; but many real-world systems have discrete-valued functions (DVFs) that do not permit gradient-based optimization. One example is the on-off thrusters that are common on spacecraft. A new technique is developed here that now extends backpropagation learning for use with DVFs. Moreover, the modification to backpropagation is small, requiring (1) replacement of the DVFs with continuously-differentiable approximations, and (2) injection of noise on the forward sweep. This algorithm is applicable generically whenever a gradient-based optimization is used for systems with discrete-valued functions. It is applied here to the control problem using on-off thrusters, as well as for training neural networks built with hard-limiting neurons (signums instead of sigmoids).

The fourth issue is that the speed of adaptation is often a limiting factor in the implementation of a neural-network control system. This issue has been strongly resolved in this research by drawing on the above new contributions: the FCA and an automatic growing of the network combine to allow rapid adaptation in an experimental demonstration on a 2-D laboratory model of a free-flying space robot. The neural-network controller adapts in real time to account for multiple destabilizing thruster failures. Stability is restored within 5 seconds, and near-optimal performance is achieved within 2 minutes. This performance is obtained despite the implementation on a serial microprocessor; implementation on parallel-processing hardware would provide dramatically-faster performance.

Principal Adviser Stephen M. Rock **Refs. 1103, 1110, 1120, 1121, 1134, 1138**

DAVID W. MEER

No. 26

Experiments in Cooperative Manipulation of Flexible Objects

Using multiple-manipulator robotic systems offers many advantages over using a single-armed robot, including increased payload capability, improved dexterity with larger objects, and expanded functionality. Most previous research with multiple-armed robot systems, however, focused on developing control strategies for the manipulation of rigid bodies. Various potential robotic applications, from the assembly of spring-loaded parts in a manufacturing environment to the servicing of satellite solar arrays in orbit, will involve the manipulation of flexible objects by multiple-manipulator systems. This thesis addresses the design of controllers for multiple-armed robotic systems grasping flexible objects, and presents experimental verification of the results.

The development of a new control policy, flexible-object impedance control, is presented. This control policy incorporates fully dynamic models of the flexible object and the robotic manipulators, and responds to environmental forces with a programmable impedance relationship for the *flexible object.*

An analysis of the stability of systems under either flexible-object impedance control or object impedance control when interacting with an arbitrary passive environment demonstrates that the inertia of the manipulators grasping the object significantly affects the stability of the coupled system. General guidelines are developed for selecting the impedance-control parameters to insure coupled-system stability.

A control policy for underactuated flexible systems, hybrid flexible-object impedance control, has also been developed and verified (in this case, only through simulation) on a simple linear system.

The flexible-object impedance controller has been incorporated into a full hierarchical control system, featuring a discrete-event-driven strategic controller, a graphical user-interface, and a real-time vision system. The enhancements required to enable the competent manipulation of flexible objects are described, including the development of a novel estimator that enabled the system to track and capture a vibrating flexible object.

Experimental results are presented throughout this thesis, validating the hierarchical control system and flexible-object impedance control on a dual-arm planar manipulator system. The results show the system tracking and capturing a vibrating flexible object and performing an assembly operation requiring the simultaneous control of the deformation of the flexible object and the interaction forces between the object and the fixture.

Principal Adviser Robert Cannon **Refs. 1100, 1119, 1128**

WILLIAM L. BALLHAUS

No. 25

Experiments in High-Performance Control of a Multi-Link Flexible Manipulator with a Mini-Manipulator

Space-based manipulator systems like the Shuttle Remote Manipulator System contain long slender links that are inherently very flexible. As a result, when moving quickly or carrying massive payloads, the links of these manipulators deflect significantly. This link flexibility slows and degrades end-point position performance and makes high-performance control of these manipulators difficult to achieve.

The research presented in this dissertation focuses on increasing the achievable slew and end-point performance of multi-link flexible manipulators through the use of a small, high-bandwidth, rigid robot (mini-manipulator) at the tip, together with direct end-point sensing. The high-bandwidth mini-manipulator can be used for rapid, precise control within a small workspace, while the main manipulator is responsible for transporting the mini-manipulator from workspace to workspace.

The overall system performance of a multi-link flexible manipulator with a mini-manipulator is limited, in part, by the ability of the flexible main arm to position quickly the mini-manipulator within the desired workspace. This is mitigated, however, by the fact that even for very high-performance control, the flexible main arm need be controlled only to an *area*, rather than to a point; an area within which the speed and precision of the mini-manipulator can then be utilized to perform the task at hand. This new generic concept of controlling to an area is pursued in this research through a new technique known as *soft terminal control.*

A new soft-terminal-control approach has been developed for multi-link flexible manipulators that exploits both the high-bandwidth local-manipulation capability and the redundancy introduced by the mini-manipulator, and the fact that the flexible main arm can be positioned more quickly to be within an area than it can be positioned to be at a point. This approach, based on a terminal-controller design, combines feedforward with feedback control. In developing this new control approach, fundamental advances were made in trajectory generation, feedback-control design, and modelling of multi-link flexible manipulators.

To aid in the development and verification of this control approach, an experimental test bed has been developed. This apparatus consists of a two-link very flexible manipulator with a mini-manipulator mounted at its tip. This system floats on an air bearing to simulate in two dimensions the zero-g, frictionless environment of space.

This dissertation contains a description of the theoretical and experimental advances made in trajectory generation, feedback-control design, and modelling of multi-link flexible manipulators. Also included are experimental results that demonstrate, for the first time, the performance advantages of a mini-manipulator and direct end-point sensing at the tip of a multi-link flexible manipulator, and of their system operation as a redundant team.

Principal Adviser Stephen M. Rock **Refs. 1088, 1092, 1094, 1099**

LAWRENCE E. PFEFFER

No. 24

The Design and Control of a Two-Armed, Cooperating, Flexible Drivetrain Robot System

Many tasks are difficult or impossible with "one-armed" robots; examples include manipulation/assembly involving long parts, and tasks requiring fine alignments or large torques. Robots with multiple manipulator-arms have the potential to do these tasks well, but only if both the manipulators and their controller are systematically designed for cooperation. This dissertation describes a design methodology and control techniques for achieving a two-armed robot system that can autonomously perform cooperative tasks in an unstructured environment. This dissertation also presents experimental results from key subsystems and of the entire robot so designed; these results validate the methodology and demonstrate the robot's capabilities.

To validate the methodology, the robot hardware and the control system have been designed concurrently, ensuring compatibility of critical properties. The hardware is specifically designed for cooperative control, incorporating the sensing and mechanical properties required. The manipulators have deliberately-exaggerated drivetrain flexibility to facilitate the study of its effects on robot cooperation. The control system is structured as a function-based, four-level hierarchy of joint, manipulator, object, and task levels, which is implemented on a multi-processor real-time computer. Each level in the hierarchy controls a different aspect of the robot's control, organizing the functions according to time-scale, and facilitating the abstraction of robotic services. The joint level handles drivetrain flexibility via joint-torque control. The manipulator level uses end-point sensing and nonlinear feedback to make each manipulator arm behave as a decoupled, multi-dimensional force/acceleration source (virtual actuator). The object level manages the object's behavior by the use of object-impedance control to achieve intimate cooperation between the two manipulators. The task level directs sequences of elemental actions to perform multi-step tasks autonomously. Experimental results are presented for each layer of control: joint, manipulator, object, and task.

The task level's results demonstrate the robot system's ability to perform multi-step, cooperative tasks autonomously, such as the "two-handed" insertion of a long part into a deep hole and a cooperative assembly with a long, fragile object — a fluorescent light bulb.

Principal Adviser Robert Cannon **Refs. 1046, 1071, 1108**

WILLIAM C. DICKSON

No. 23

Experiments in Cooperative Manipulation of Objects By Free-Flying Robot Teams

Free-flying space robots are envisioned as a key element of our long-term presence in space. These robots could perform many of the dangerous and expensive extra-vehicular activity (EVA) tasks that presently require humans. Astronauts on the ground or in a nearby spacecraft could provide to the robots high-task-level direction of the activities from the safety of a pressurized environment. Certain missions in space may require the use of two or more robots working together as a team. As an example, a team of robots could be used to capture an orbiting satellite and provide transportation of the satellite to the shuttle, where astronauts or the robots themselves could make repairs.

This dissertation makes several contributions to the control of objects by a team of robots in space. To verify these contributions, laboratory experiments have successfully demonstrated a team of free-flying robots capturing, transporting, and docking a large, freely moving object. In these experiments, the object and robots float on a thin cushion of air over a granite surface plate, simulating with high fidelity in two dimensions the drag-free, zero-gravity conditions of space. A human user indicates easily a desired object location and orientation through a graphical user interface. The robots then capture and so position the object, with no additional input required from the user. On command, the robot team docks the captured object with a second (stationary) object.

This dissertation presents the AUTOMAN (AUtonomous robot-Team Object MANipulation) hierarchy developed in this research as a framework for providing object-based task-level control of a system that uses a team of independently operating robots. The AUTOMAN hierarchy implements a carefully chosen set of interfaces between the various elements of the distributed-computation system that maximizes the autonomy of the robots—under the constraint that the robots must provide cooperative control of a common object.

A Decentralized Object-Impedance Controller was developed to allow a team of independently operating robots to work as a team to cooperatively manipulate a common object. The communication interface between a central coordinating processor and the robots is a low-bandwidth specification of a desired object trajectory and a programmable impedance relationship between the object's motion and external forces. This low-bandwidth interface between the robots and the central processor is an advancement over the original Object-Impedance Controller that required a high-bandwidth communication interface.

Addressing the low-level control of the robots themselves, this dissertation presents the Hybrid-Dynamics controller that uses a novel control approach to assimilate both discrete-valued actuators (such as the on-off thrusters used by the experimental robots) and continuous-valued actuators (such as motors) in system applications requiring precise control.

The Subsystem-Merging dynamic modelling method has been developed for producing a system model directly from subsystem descriptions. This method takes advantage of simple kinematic relationships to merge subsystem descriptions into a full system model with no need for decomposing the subsystems. The resulting system model is expressed in terms of the subsystem descriptions; thus the model can be interpreted symbolically as well as numerically. This novel modelling technique provided the basis for the stability analyses and total system design of the closed-loop object/robot-team system presented in this dissertation.

Principal Adviser Robert Cannon **Refs. 1094, 1139, 1147**

LARRY J. ALDER

No. 22

Control of a Flexible-Link Robotic Arm Manipulating an Unknown Dynamic Payload

When light-weight space-based robots, such as the space shuttle's RMS (remote manipulator system), manipulate massive payloads such as satellites, significant structural bending is induced in the links of the robot. In addition, space-based robots will often manipulate payloads that are not rigid bodies: for example, satellites may contain fuel or have flexible appendages. This dissertation contributes new basic technology that will enable flexible-link manipulators to perform precise end-point control of payloads while simultaneously controlling the unknown internal dynamics of the payloads.

The approach taken here combines high-performance control with an innovative identification algorithm. In addition, in order to aid in the development of control and identification routines, a modular modelling method was employed that allows the equations of motion of the payload and arm to be generated separately and then merged, in a numerically efficient manner, to yield an accurate system model.

First, controllers incorporating end-point feedback with a known payload are made robust to high-frequency modelling errors, sensor noise, and sensor biases using frequency-weighted linear quadratic gaussian design methods. Using end-point position measurements as the primary sensor, the robot is then capable of actively damping the internal payload dynamics an order of magnitude faster than the natural damping rate—if it knows the payload parameters. However, with this type of controller small parameter variations in the payload can lead to poor performance or instability.

This research has therefore also developed an identification algorithm that updates the end-point controller parameters; this enables the system to achieve high performance when the payload dynamics are not known apriori. By using a nominal control law, the identification problem can be reduced to detecting and identifying eigenvalues of a closed-loop system. To identify these eigenvalues, a generic algorithm capable of determining the eigenvalues of a system in real time has been developed: even the order of the system need not be known in advance. With this approach, moreover, the identification algorithm does not require that the system inject broad-band excitation in order to work accurately.

An experimental robotic system was designed and built to test these emerging control strategies. All of the control strategies have been verified on the experimental robot. Experimental results demonstrate, for the first time, precision end-point control of a very flexible single-link robot arm with unknown dynamic payloads.

Principal Adviser Stephen M. Rock **Refs. 1086, 1094, 1096, 1102, 1160**

VINCENT WEI-KANG CHEN

No. 21

Experiments in Nonlinear Adaptive Control of Multi-Manipulator, Free-Flying Space Robots

Sophisticated robots can greatly enhance the role of humans in space by relieving astronauts of low level, tedious assembly and maintenance chores and allowing them to concentrate on higher level tasks. Robots and astronauts can work together efficiently, as a team; but the robot must be capable of accomplishing complex operations and yet be easy to use. Multiple cooperating manipulators are essential to dexterity and can broaden greatly the types of activities the robot can achieve; adding adaptive control can ease greatly robot usage by allowing the robot to change its own controller actions, without human intervention, in response to changes in its environment. Previous work in the Aerospace Robotics Laboratory (ARL) have shown the usefulness of a space robot with cooperating manipulators. The research presented in this dissertation extends that work by adding adaptive control.

To help achieve this high level of robot sophistication, this research made several advances to the field of nonlinear adaptive control of robotic systems. A nonlinear adaptive control algorithm developed originally for control of robots, but requiring joint positions as inputs, was extended here to handle the much more general case of manipulator endpoint-position commands. A new system modelling technique, called *system concatenation* was developed to simplify the generation of a system model for complicated systems, such as a free-flying multiple-manipulator robot system. Finally, the *task*-space concept was introduced wherein the operator's inputs specify only the robot's *task*. The robot's subsequent autonomous performance of each task still involves, of course, endpoint positions and joint configurations as subsets.

The combination of these developments resulted in a new adaptive control framework that is capable of continuously providing full adaptation capability to the complex space-robot system in all modes of operation. The new adaptive control algorithm easily handles free-flying systems with multiple, interacting manipulators, and extends naturally to even larger systems.

The new adaptive controller was experimentally demonstrated on an ideal testbed in the ARL—a first-ever experimental model of a multi-manipulator, free-flying space robot that is capable of capturing and manipulating free-floating objects without requiring human assistance. A graphical user interface enhanced the robot usability: it enabled an operator situated at a remote location to issue high-level task description commands to the robot, and to monitor robot activities as it then carried out each assignment autonomously.

Principal Adviser Robert Cannon **Refs. 1082, 1094, 1116, 1117, 1131, 1173**

MARC ULLMAN

No. 20

Experiments in Autonomous Navigation and Control of Two-Armed Free-Flying Space Robot

Although space presents an exciting new frontier for science and manufacturing, it has proven to be a costly and dangerous place for humans. It is therefore an ideal environment for sophisticated robots capable of performing tasks that currently require the active participation of astronauts. The Aerospace Robotics Laboratory, working in cooperation with NASA, has developed an experimental model of a multi-manipulator, free-flying space robot that is capable of capturing and manipulating free-floating objects without requiring human assistance.

The experimental robot model uses air-cushion technology to simulate, in 2-D, the drag-free, zero-g characteristics of space. It is a fully self-contained vehicle/manipulator system equipped with gas-jet thrusters for motion control, two two-link manipulators fitted with grappling end-effectors, an electrical power system, digital and analog I/O capabilities, high-speed vision, and a multi-processor real-time computer. These subsystems have been carefully integrated in a modular architecture that facilitates maintenance and ease-of-use.

A sophisticated control system has been designed and implemented to manage and coordinate the actions of the various component subsystems. A custom on-board vision system is used for closed-loop endpoint control and object tracking in the robot's local reference frame. A multi-camera off-board vision system provides global positioning information to the robot via a wireless communication link. Successful rendezvous, tracking, and capture of free-floating, spinning objects is facilitated by simultaneously controlling the robot base position and the manipulator motions. These actions are coordinated by a novel event-driven finite-state machine that processes both transient events and multi-valued stimuli possessing state (internal memory).

A graphical user interface enables an operator situated at a remote location to provide high-level task description commands to the robot, and to monitor the robot's activities while it carries out these assignments. The user interface allows a task to be fully specified before any action takes place, thereby eliminating problems associated with communications delays.

The success of this project was predicated on viewing it first and foremost as a systems engineering problem. A design philosophy that emphasized maintaining a *systems perspective* while utilizing a *modular implementation* served to guide virtually every phase of its development. This approach to systems engineering is expounded upon in the early chapters of the thesis and contributes to the general applicability of the concepts and ideas presented in the remainder of the document.

Principal Adviser Robert Cannon **Refs. 1066, 1073, 1082, 1087, 1094, 1095, 1105**

ROBERTO L. VASQUEZ

No. 19

Experiments in Two-Cooperating Arm Manipulation From a Platform with Unknown Motion

Conventional robotic control systems assume the robot to be rigidly mounted to an inertially fixed platform. To expand the application of robots, both on earth and in space, the robots must be made fully usable even if mounted on a moving platform. For example, some space applications will require that a *small* (perhaps human-sized) pair of cooperating robotic arms be mounted at the end of a *large* space manipulator. To achieve deft endpoint manipulation, the control system must do work on a separate object perfectly, independent of oscillations of its own base induced by the inherent flexibility of the large manipulator. Not achieving full independence from its base motions can lead to severe performance degradation.

Another example is a robot working on a ground-fixed object from a rocking truck.

This dissertation makes several contributions to the effective control of single and cooperative manipulators situated on a moving platform. In particular, an extended computed-torque controller is developed. This controller does not require direct sensing of platform position or velocity: a practical attribute. (In practice, the platform position and velocity are difficult to measure, and these signals are thus often unavailable.)

Two types of system coupling are considered: one-way coupling and two-way coupling. In a system with one-way coupling, the platform motion is not affected by manipulator motions; but, manipulator motions are affected by their dynamic coupling to the platform (e.g., a truck). In a system with two-way dynamic coupling, the platform motion and manipulator motions are each affected by the other: they are totally coupled dynamically (e.g., small arms at the end of a long, limber boom). Formulations of dynamic controllers for manipulators mounted on each type of moving platform are developed. An interesting aspect of the problem is that driven-platform oscillation produces parametric excitation of the (two-link) arm's motion.

The dissertation also presents multiple-manipulator cooperative control from a moving platform. This has been achieved, for the first time, (and demonstrated experimentally) by combining the extended computed-torque controllers with a high-level object-impedance controller.

Finally, the Sensitivity Map is introduced. The Sensitivity Map is a graphical representation that indicates regions in operational space where the manipulator endpoint is most sensitive to base accelerations. In particular, for example, the map enables the designer to determine regions in the workspace where given endpoint position performance specifications can be met even when base acceleration is measured.

The control strategies designed here have been experimentally verified on a pair of planar, cooperating manipulators situated on a light-weight, spring-mounted moving platform.

Principal Adviser Robert Cannon **Refs. 1060, 1078, 1110**

CELIA MARIE OAKLEY

No. 18

Experiments in Modelling and End-Point Control of Two-Link Flexible Manipulators

Current space manipulators employ control schemes that are severely limited by structural rigidity requirements. As a result, tasks are executed slowly and tediously. The goal of this research is to increase the performance of flexible manipulators by developing modelling techniques and control strategies that overcome these limitations.

Toward this goal, nonlinear equations of motion for two-link structurally-flexible manipulators were developed using the assumed-modes method. A novel approach for representing the link deflections, called the *System Modes Representation*, was developed, to realize fully the advantages of the assumed-modes method. It produced an accurate, low-order model. Accuracy gained with this modelling technique improved controller performance.

The manipulator model was used to design a variety of controllers—two are fully contrasted. The baseline controller is a conventional proportional-plus-integral-plus-derivative (PID) joint controller based on joint angle and joint rate measurements. The performance of this type of control is severely limited because the sensors are located coincident with the actuators.

Direct measurement of the manipulator end point can be used to overcome the limitations of joint control. End-point measurements were integrated into a controller design based on linear-quadratic Gaussian (LQG) theory. The end-point controller improved, in some cases by an order of magnitude, the trajectory tracking and disturbance rejection capabilities of the baseline controller.

An experimental two-link flexible manipulator, supported by air cushions on a smooth horizontal surface, was designed and constructed to verify and refine the modelling and control strategies.

Principal Adviser Robert Cannon

Ref. 1063, 1070, 1071, 1074, 1077, 1080

ROBERTO ERNESTO ZANUTTA

No. 17

Experiments in Adaptive Control of Cooperating Manipulators

A robot's capability to carry out complex tasks can be greatly increased by the use of multiple cooperating manipulators. To make the control of such robots robust and safe the robots must have the capability to identify the dynamic properties of the objects under manipulation and, based thereon, continually select control-parameter values appropriately, all in real time. The process of identifying an object's parameters while simultaneously controlling it in real time is called adaptive control.

This dissertation presents strategies developed for achieving adaptive control using co-operative manipulators. Experimental results are presented for each strategy.

The basic control algorithm used for this work is the object impedance controller (OIC). This controller has already been shown to lead to good overall strategies for coordinating multiple manipulators when the dynamics of the object under manipulation are known. *In this dissertation the OIC approach is extended to the control of objects whose dynamics are not known.* Several techniques for controlling cooperative manipulator systems using adaptive control are developed and evaluated. The OIC is used in conjunction with identification strategies to make the overall controller account for the unknown mass dynamics of the manipulated objects.

The identification is done using two methods: in the first, force sensors at the grasp points are used in combination with recursive least squares to solve for the dynamics of the object; in the second, the object's dynamics are estimated from the trajectory errors of the object. Both of these methods were found to yield substantially better results than for the case of no object information; but each of these first two methods has minor drawbacks, which led to the development of a third method.

The adaptive OIC using the force sensors with a model of the object dynamics showed considerable improvement in trajectory following over non-adaptive control. The method though has two drawbacks: i) during the initial phase of a trajectory, information must be gathered; therefore, the early controller performance is the same as with no information, and ii) sudden changes in the parameters of the object lead to "step input" types of response in some cases.

The OIC using object dynamics estimated from trajectory error also showed much better trajectory following than non-adaptive control. The method was derived using Lyapunov theory with the simultaneous consideration of trajectory following and parameter identification. The trajectory errors were decreased during the entire trajectory, including the beginning. The only shortcoming was that the parameter estimates *per se* were poorer than with the previous method.

A third version of the adaptive OIC was developed in which the two previous methods were combined. This method yielded good trajectory following during the entire slew and good parameter estimates as well.

Principal Adviser Robert Cannon

ROSS KONINGSTEIN

No. 16

Experiments in Cooperative-arm Object Manipulation with Free-Flying Robot

Developing computed-torque controllers for complex manipulator systems using current techniques and tools is difficult because they address the issues pertinent to simulation, as opposed to control. This dissertation presents a new formulation of computed-torque (CT) control that leads to an automated computed-torque robot controller program. This automated tool is used for simulations and experimental demonstrations of endpoint and object control from a free-flying robot.

A new computed-torque formulation states the multibody control problem in an elegant, homogeneous and practical form. A recursive dynamics algorithm is presented that *numerically* evaluates kinematics and dynamics terms for multibody systems given a topological description. Manipulators may be free-flying, and may have closed-chain constraints. With the exception of object squeeze-force control, the algorithm does not deal with actuator redundancy. The algorithm is used to implement an automated 2D computed-torque dynamics and control package that allows joint, endpoint, orientation, momentum and object squeeze-force control. This package obviates the need for hand-derivation of kinematics and dynamics, and is used for both simulation and experimental control in the course of this research.

Endpoint control experiments are performed on a laboratory robot that has two arms to manipulate payloads, and uses an air bearing to achieve very-low drag characteristics. The robot's base body mass and inertia are considerably larger than that of the manipulator arm segments, much like NASA's proposed Orbital Maneuvering Vehicle. Simulations and experimental data for endpoint and object controllers are presented for the experimental robot – a complex dynamic system.

There is a certain *rather wide* set of conditions under which CT endpoint controllers can neglect robot base accelerations (but not motions) and achieve comparable performance to including base accelerations in the model. The regime over which this simplification holds is explored by simulation and experiment. These simplifications can result in a savings of an *order of magnitude* of computation in the controller.

Momentum control via external forces and torques (e.g., thrusters) is provided for in the formulations, but is not done in this study.

Principal Adviser Robert Cannon **Refs. 1066, 1085, 1148**

BRIAN LEE ANDERSEN

No. 15

Experiments in End-Point Position and Force Control of a Minimanipulator on a flexible-Drive Manipulator

This research comprises an experimental study of how to use a minimanipulator carried by a flexible main manipulator to control rapidly and precisely either the tip position or the force applied to the environment. Most robotic tasks entail a great deal of manipulation in a few localized workspaces. A minimanipulator can be used to perform these tasks in the localized workspace at a much higher bandwidth and precision than can be achieved by the main manipulator alone, especially when the main manipulator is flexible.

Minimanipulators do, however, present new challenges in the design of a control algorithm because the coupling between the main and minimanipulators can be complex. This research has developed a method for designing control algorithms for the minimanipulator in which — under a wide range of conditions — the dynamics of the main manipulator need not be included. Only the disturbance that the minimanipulator produces on the main manipulator must be computed in order to determine whether the main manipulator will take the minimanipulator out of range of its desired position.

Traditional controller implementations require switching from a position control mode to an entirely different controller when the manipulator comes into contact with its environment and is required to regulate the applied force. This research shows that the need to switch control modes can be avoided: the same controller used to regulate tip position when the manipulator is out of contact can be used when the manipulator is in contact to regulate tip position with the addition of an outer loop that uses force errors to adjust the commanded position for the inner loop. This obviates the need to design an entirely different controller for when the manipulator is in contact.

The behavior of the manipulator when coming into contact with the environment depends both on the state of the tip of the manipulator at the moment of contact and on the controller used. Approaching a target without considering the dynamics of coming into contact could cause the manipulator to bounce away from the target. A simplified model of the problem of contact is analyzed to determine what conditions are important to insure smooth contact.

The procedures generated by this research were implemented using a two-link planar manipulator having flexible tendon drives and a minimanipulator at its tip. Experimental results are presented for the rapid, precise positioning of the tip, for regulation of force when in contact with the environment, and for achieving smooth, well-controlled contact without controller switching.

Principal Adviser Robert Cannon

WARREN J. JASPER

No. 14

Experiments in Thrusterless Robot Locomotion Control for Space Applications

While performing complex assembly tasks or moving about in space, a space robot should minimize the amount of propellant consumed. This thesis comprises an analytical and experimental study of space robot locomotion and orientation without the use of thrusters. The goal of this research is to design a robust control paradigm that will perform thrusterless locomotion between two points on a structure, and to implement this paradigm on an experimental robot.

A two-arm free-flying robot has been constructed which floats on a cushion of air to simulate in two dimensions the drag-free, zero-g environment of space. The robot can impart momentum to itself by pushing off from an external structure in a coordinated two-arm maneuver, and can then reorient itself by activating a momentum wheel.

The controller design consists of two parts: a high-level strategic controller and a low-level dynamic controller. The strategic controller, implemented as a finite-state machine, monitors the state of the system and switches control laws asynchronously, based on discrete events. Different specific control laws are implemented depending upon the configuration of the system, the number of degrees of freedom, and the desired task. The dynamic controller consists of a system of estimators, control laws, trajectory generators, and filters. For example, whenever both arms are grasping an external structure, the strategic controller installs a momentum controller which causes the linear and angular momentum of the *system* to follow desired trajectories.

The control paradigm has been verified experimentally by commanding the robot to push off from a structure with both arms, rotate 180 degrees while translating freely, and then catch itself on another structure. This method, based on the idea of *computed torque*, provides a linear feedback law in momentum and its derivatives for a system of rigid bodies. By controlling momentum, a configuration-independent quantity, the robot can leap precisely from one place to another, while accounting for nonlinear forces and changing kinematic constraints. It is believed that this design approach can be easily extended to three dimensions and to more complex robot configurations.

Principal Adviser Robert Cannon **Refs. 1053, 1079**

CHRISTOPHER RICHARD UHLIK

No. 13

Experiments in High-Performance Nonlinear and Adaptive Control of a Two-Link, Flexible-Drive-Train Manipulator

Excitation of flexible drive system resonances severely limits the performance of most present-day robotic manipulators. This dissertation discusses the development and experimental verification of advanced high-performance adaptive control strategies for high-speed, lightweight, nonlinear manipulators in which the flexibility resides primarily in the drive system.

Several techniques for controlling nonlinear, flexible systems are developed and evaluated. Computed torque concepts are extended to cover equations of motion typical of flexible drive-train manipulators. Continuous-time control strategies are found to require very high sample rates that limit the applicability of computed torque to flexible systems. To overcome this sample rate problem, the computed torque controller is modified to generate feedforward-only trajectories while GSLQR (Gain Scheduled Linear Quadratic Regulator) and CGEKF (Constant Gain Extended Kalman Filter) are used for feedback control. Gains are scheduled as a function of configuration and payload mass to achieve more uniform performance across the workspace. Inverse-dynamics techniques are used to inject the reference and to calculate feedforward commands for accurate trajectory tracking.

An innovative mass identifier is used to adapt to rapid payload mass variations. The identifier estimates the payload by comparing the forces in the elastic drive train with the accelerations of the payload mass. This payload mass estimate is found to be very sensitive to the accuracy of the manipulator model. A technique is developed to gain very high estimation speed and accuracy, despite this sensitivity. With this new technique, the payload estimate is acquired quickly enough to be useful for safely speeding up the desired trajectory for light-weight payloads. This results in great time savings over conservative, safe trajectories. Moreover, the payload mass estimator is sensitive and quick enough to recover from potential instabilities when, for example, a heavy payload is unexpectedly dropped.

Principal Adviser Gene F. Franklin **Ref. 1055**

STANLEY A. SCHNEIDER

No. 12

Experiments in Dynamic and Strategic Control Of Cooperative Manipulators

This thesis comprises an experimental study of a semi-autonomous robotic system with multiple manipulators. Four topics are studied in detail: hierarchical real-time system design, conceptual operator command, dynamic control of cooperative manipulators, and integrated real-time vision. The goal is to study *simultaneously* the dynamic and strategic issues of cooperative robotic manipulation. This work focuses not only on the various subsystems, but also on their interfaces and interactions.

The system is structured as a four-level hierarchy. At the highest level, an iconic "object-only" user interface allows an operator to direct the conceptual activities of the system. The operator commands only object motions; the arm actions required to effect these motions need not be specified.

An event-driven tabular finite state machine provides strategic command. This technique encourages modular design of multi-process programs, provides an intuitive task programming environment, and naturally manages the concurrent system interactions.

The dynamic controller implements "object impedance control"—an extension of the impedance control concept to cooperative-arm manipulation of a single object. This controller presents an intuitive *object behavior* specification interface, and provides good dynamic performance both for free-motion positioning and environmental contact tasks.

A real-time point-tracking two-dimensional vision system locates and tracks passive targets. Groups of targets can be identified and tracked as individual objects. The system can track multiple objects at 60 Hz with sub-millimeter resolution.

The design was verified by experimental implementation: a multi-processor real-time computer controls a dual-arm planar manipulator system. Experimental results are presented, showing the system locating and identifying a moving object, catching it, and performing a simple cooperative assembly. These operations are controlled by a remote user entering only high-level conceptual object relations. Results from dynamic control experiments show excellent dynamic trajectory tracking performance, while also permitting control of environmental contact forces.

Principal Adviser Robert Cannon **Refs. 1065, 1069, 1075, 1082, 1091, 1104, 1109, 1111, 1116, 1124, 1129, 1130, 1131, 1172, 1173**

RAY KRAFT

No. 11

Experiments in End-Point Control of a Flexible Robot with a Mini-Manipulator

The speed and precision of present day robots is limited by both manipulator size and flexibility. Robots that are required to operate over a large workspace are naturally large in size, and precisely controlling the end-point of such a large manipulator is complicated by mechanical amplification of joint motions. Also, given that all robots have some degree of flexibility, the standard method of using collocated sensing and actuation means that the end-point position is not precisely known.

Direct end-point position and force control of a large flexible manipulator equipped with a quick, lightweight, rigid mini-manipulator is examined in this dissertation. By directly measuring the end-point position and force, errors due to flexibility are eliminated, and much faster performance is possible. Through the use of a mini-manipulator, the problem of mechanical amplification is also solved; moreover, it is also possible to bypass bandwidth limitations imposed by flexibility. Thus, it becomes possible to increase further — by another order of magnitude — the quickness and precision of manipulation.

Another serious problem is inherent nonlinearity: the mini-manipulator is a five link, closed kinematic chain. A method is developed in this thesis for mapping the highly non-linear, Multi-Input-Multi-Output mini-manipulator into a set of multiple, approximately linear, Single-Input-Single-Output systems, and the resulting linear systems are identified. Next, an LQG controller is developed to control the set of linear systems. Finally, the linear control law outputs are then mapped back into the set of control torques that are meaningful, and therefore effective, for control of the actual nonlinear system itself.

Finally, a surface-following algorithm is developed. This algorithm allows the manipulator system to traverse the contours of a target surface by "feeling" its way along, while at the same time controlling the force that the manipulator exerts normal to the surface. In a full, experimental demonstration, tracking speeds between 0.5 and 4.0 cm/sec with force maintained at 20 or at 40 grams force, with 4% RMS error are achieved. The algorithm is fairly robust, and even allows the manipulator to move in and out of corners.

Principal Adviser Robert Cannon **Refs. 1045, 1054, 1083**

MICHAEL HOLLARS

No. 10

Experiments in End-Point Control of Manipulators with Elastic Drives

Excitation of lightly-damped drive system resonances severely limits the performance of most present-day robotic manipulators. This dissertation discusses the development of practical high-performance control strategies for manipulators in which the flexibility resides primarily in the drive system. To test the control strategies, an experimental two-link planar manipulator has been constructed that exhibits very lightly-damped drive system resonances, highly nonlinear dynamics, and large variations in payload mass.

Three different control strategies are examined. First, a standard collocated proportional-integral-derivative (PID) controller is implemented to demonstrate baseline performance that is characteristic of current industrial robots. What is found is that the control bandwidth is absolutely constrained to less than half the cantilever or fundamental hinged-mode vibration frequency of the manipulator, rejection of disturbances is poor, and large steady-state end-point positioning errors occur due to friction, gravity loading, and other unmodeled dynamics.

Linear-quadratic-Gaussian (LQG) control techniques are then used to develop a high-performance controller that employs noncollocated end-point position sensing and a configuration-specific model of the manipulator. When the system is at or near the design configuration, the control bandwidth, disturbance rejection, and steady-state errors are improved by a factor of about four over those for the collocated PID designs. However, the highly tuned LQG controller rapidly loses performance as the arm geometry and payload mass vary from the design point, and deteriorates to instability for some arm geometries and payload masses.

To reduce sensitivity to the change in geometry, a constant-gain extended Kalman filter (CGEKF) coupled with a linear-quadratic-regulator (LQR) is developed in which the state estimates are propagated by integrating the full nonlinear equations of motion. The nonlinear CGEKF/LQR controller exhibits exceptional robustness to modeling errors, at least a factor-of-four improvement in bandwidth, disturbance rejection, and positioning accuracy over the PID design, excellent command trajectory following with little or no overshoot, and stable control over the *entire* workspace of the manipulator. An important feature of the CGEKF/LQR is its entirely discrete design. A sample rate of only ten times the closed-loop bandwidth is used to implement the controller.

Principal Adviser Robert Cannon **Refs. 1042, 1049, 1056, 1067, 1068, 1076**

HAROLD ALEXANDER

No. 9

Experiments in Control of Satellite Manipulators

Experiments are discussed in the control of freely-floating space robot manipulators. A physical laboratory model of a one-armed space robot was built and controlled that floats freely on an air bearing over a very flat granite surface plate.

A new method is presented for space robot control that is based on the operational-space or resolved-acceleration method developed for industrial style manipulators. The new extended version makes allowance for the dynamic reaction of the freely-floating robot body when the manipulator is moved, so that precise specified end-effector accelerations *in space* may be achieved in spite of the lack of a fixed manipulator base.

A mathematical dynamic model is developed for the laboratory robot and the extended control method is experimentally applied to the robot with command of straight-line slews between points fixed in inertial space. Successful trajectory tracking and position regulation are demonstrated independent of the orientation of the command reference frame with respect to the free-floating robot body.

The potential of the extended operational space method for non-manipulator control applications is discussed. The extension to three-dimensional space robot control is introduced as well as applications involving multi-manipulator robots and multiple robots.

The stability of model-based control methods such as operational space and computed torque is discussed. A standing conjecture regarding stability of computed-torque control for large velocity gains is refuted, and a more narrow stability theorem is proven for limited generalized velocities. The groundwork is thus laid for a similar proof regarding operational-space control.

Principal Adviser Robert Cannon **Refs. 1051, 1052, 1056, 1057, 1081**

DANIEL ROVNER

No. 8

Experiments in Adaptive Control of a Very Flexible One Link Manipulator

This thesis describes experiments conducted to advance the science of adaptive control as applied to mechanical systems with distributed flexibility, very low inherent damping, and non-collocated sensors and actuators. The experimental apparatus employed is a very flexible one link robotic manipulator. A DC motor applies torque at the manipulator hub in order to position the opposite end. End-point position is directly measured by an optical sensor separated from the actuator by flexible structure. Loads grasped by the manipulator's end effector cause abrupt changes in the dynamics of the system. The adaptive controllers described in the thesis maintain stable, high-bandwidth tip position control by adjusting themselves to compensate for these changes.

Self-Tuning Regulator algorithms are developed in which the controller explicitly identifies system models from input/output data and uses them in a subsequent control law design step. The sensitivity of pole placement and Linear Quadratic Gaussian control law design to identification inaccuracies is examined. The experimental performance of identification algorithms is then discussed in the context of the accuracy required for control law design.

Identification techniques based on minimization of equation error give good results, but it is essential that their sensitivity to high frequency noise and sample rate be compensated. This fact has generally been overlooked in previous literature on identification of flexible structures. Alternative approaches based on minimization of output error perform poorly, probably due to the existence of local minima in the performance index.

The performance of an adaptive controller using a modified least squares identification algorithm and a pole placement control law design algorithm is demonstrated. This controller's performance is limited by the necessity of providing a strongly-exciting input signal to achieve accurate system identification.

A novel identification algorithm is proposed and demonstrated that directly estimates the physical parameter subject to variation, in this case the mass of the manipulator load. Extensions of the technique to other parameters and to more than one parameter are indicated. An adaptive controller based on this identification algorithm and LQG control law design is implemented on the experimental flexible manipulator. Adaptation to a load change causing a 40% decrease or 60% increase in manipulator moment of inertia is demonstrated during a commanded step change of position. Under identical conditions, when the system was operated with a conventional fixed-gain controller it became unstable.

Principal Adviser Robert Cannon **Refs. 1061, 1064**

MICHAEL SIDMAN

No. 7

Adaptive Control of a Flexible Structure

The demonstration of a high-performance adaptive control system for a lightly-damped flexible mechanical structure, such as found in large space structures, lightweight robots and computer peripherals, is discussed.

The system accurately identifies the frequencies of three resonances and one anti-resonance, as well as the overall gain of the experimental plant, the Stanford Four Disk System. The robustness and reliability of the system have been demonstrated in the presence of large, sudden changes in plant dynamics that include a complex pole-zero flip and near pole-zero cancellation that occur as payload mass is added to the system.

Fixed-gain robust control performance, both colocated and non-colocated, is compared to non-colocated adaptive control performance. The tuned adaptive controller demonstrates the highest levels of active damping and disturbance rejection and the best response to reference-input commands. Further, the adaptive system can tune to changes in mass and stiffness anywhere in the plant.

New methods that make use of limited *a priori* knowledge of the plant not only greatly improve the quality of the identification in the presence of measurement noise, high-frequency unmodeled dynamics and low-frequency disturbances, but greatly reduce the number of parameters that need to be identified. The methods make use of known plant dynamics invariant to changes in mass and stiffness, frequency bands where unknown, modeled resonant dynamics exist and the natural damping of such dynamics. With these techniques, the identification rapidly converges to very accurate plant estimates with greatly reduced computational requirements.

A new method of pole-placement ensures excellent reference-command step response, substantial active damping of modeled modes, modest amounts of control effort and low computational intensity despite major changes in plant dynamics. The pole-placement dynamically computes closed-loop poles to dampen resonant plant poles without changing their natural frequencies.

New techniques ensure stable control, at least a minimum level of performance at all times and fast recovery after large sudden changes in plant parameters that occur even while the plant is in a quiescent state. These include a controller structure that ensures bumpless transfer between leapfrogging polynomial-based adaptive compensators, a standby robust colocated compensator and a method that automatically adds bandlimited perturbation to the system to facilitate fast identification with minimal effect on plant output.

Principal Adviser Gene F. Franklin **Ref. 1047**

WEN-WEI CHIANG

No. 6

Rapid Precise End Point Control of a Wrist Carried by a Flexible Manipulator

The speed and accuracy of a robot manipulator can be increased by using end-point sensors for motion measurement and control, along with an accurate dynamic model of the mechanical system in the control algorithm. However, the closed-loop control bandwidth of a robot manipulator is still physically limited ultimately by its structural flexibility, since the end effector and the actuator are separated [SCH-1].

A minimanipulator can be added to the end of a main robot arm to perform special tasks with high accuracy and bandwidth, and thus enhance the robot's performance [CRO-1,ROV-1,SAL-1,SHA-1]. However, dynamic interaction between the minimanipulator and the structural flexibility of the main robot arm may tend to destabilize the system, making the control design very difficult. Unless the design properly accounts for this interaction, stable control bandwidth will be limited to below the first structural mode frequency [SHA-1].

In the research described by this thesis, analyses were performed to study the dynamic interaction between the motion of a minimanipulator and the structural flexibility of the main robot arm. A general geometric relation between sensor and center of percussion was found which assures that the dynamic interaction will be stable. A simple controller design will be insensitive to modeling uncertainty while achieving high performance, when a suitably placed end-point sensor is used to measure the motion of the end effector carried by the minimanipulator.

A plane-motion mechanical system has been built to demonstrate several fast maneuvers of such a mini-macro manipulator system. The mechanical system consists of a 16.5 *cm.* rigid link as a minimanipulator, which is carried by a 96.8 *cm.* very flexible beam. Control bandwidth achieved for the minimanipulator is several times higher than the beam's first structural frequency.

A new frequency identification scheme has also been developed and implemented successfully in a closed-loop adaptive control of a separate mechanical laboratory system consisting of two inertia disks connected by a torsional rod [CHI-1]. It is believed that the same frequency-identification scheme can be used to improve further the performance of the mini-macro manipulator system when adaptive control is employed.

Principal Adviser Robert Cannon **Ref. 1041, 1083**

JAMES MAPLES

No. 5

Force Control of Robotic Manipulators With Structural Flexibility

Two fundamental problems in the control of robotic manipulators are addressed in this dissertation: 1) controlling contact force at one end of a flexible structure by exerting torque at the opposite end, and 2) managing the switching transitions that occur when changing control regions, especially when changing from controlling position to controlling contact force.

This research establishes and demonstrates experimentally that: 1) it is possible to achieve good closed loop force control of a flexible manipulator using *end-point feedback* (that is, directly measuring the quantity of interest at the tip of the manipulator and using this measurement as the primary source of feedback control), 2) the limit to the performance of such a system is due to the wave propagation time for the flexible structure, 3) for a given manipulator and target, the initial force overshoot is a function only of the approach velocity, 4) switching between control regions can be easily accomodated by switching algorithms developed in this research, and 5) under some circumstances, it is possible to have a sustained or unstable bouncing condition, even when proper control algorithms are applied and switched. Supplemental algorithms to avoid bouncing and to recover, should bouncing occur, are developed and demonstrated.

Results from this research are experimentally verified on a very flexible (0.5 Hz) single link manipulator. The manipulator consists of a one meter long aluminum-element beam that has been constructed to be flexible in bending while maintaining stiffness in torsion. One end of this beam is attached to a DC torque motor that can be controlled so as to precisely position the opposite end (the "tip") of the beam. In addition, the tip of the beam can be brought into contact with a target object and the level of contact force can be measured and controlled.

Specific experimental demonstrations include a maneuver in which the flexible arm is slewed rapidly to contact a moving target, switching smoothly from optical end-point position control to end-point contact-force control.

Principal Adviser Robert Cannon **Ref. 1044**

ERIC SCHMITZ

No. 4

Experiments on the End-Point Position Control Of a Very Flexible One-Link Manipulator

An experiment has been constructed to demonstrate control strategies for the next generation of fast-moving and lightweight industrial robots as well as for future manipulators for space applications: it consists of a one link, one meter long, very flexible manipulator in which the position of one end (*tip*) is to be sensed and precisely positioned by torquing at the *other* end. The arm is moving and bends freely in the horizontal plane but is stiff in torsion and vertical bending. For such a situation, where the sensor used for feedback and the actuator are separated by a flexible structure (*non-colocation*), the problem of achieving stability is severe.

After a description of the dynamic modelling of the arm and of the experimental apparatus, the application of classical and modern control design techniques to the design of a tip position controller is discussed. It is shown that good stability can be obtained with a closed-loop bandwidth that is effectively two times the frequency of the fundamental cantilevered mode of the arm ($f_c = 0.5$ Hz). The main advantages of tip-position versus joint-angle feedback are higher precision on tip positioning, faster recovery from external tip disturbance forces and the capability to achieve target tracking. The nonminimum phase transmission zeros of the open-loop transfer function from torque to tip-position output limit the ultimate bandwidth of the tip-position loop. An increase in the position bandwidth has to be traded-off versus a decrease in the stability margins of the tip-position loop. The nonminimum phase zeros have the same effect as an equivalent time delay equal to about $\frac{1}{10}$ of the period of the fundamental cantilevered mode of the experimental arm. This equivalent delay includes a pure time delay that is interpreted as the time for a bending wave to travel the length of the beam.

Good closed-loop performance is strongly dependent on the addition of auxiliary colocated sensors (hub-rate and strain-gauge mounted close to the actuator) to the primary tip-position sensor. Excellent agreement has been obtained between experimental and simulated time responses.

A fixed-gain reduced-order compensator that is robust to changes in the arm payload has been successfully implemented.

A scheme for switching smoothly between control using an end-point position sensor and control using a colocated joint-angle sensor has been designed and demonstrated for large angle slew maneuvers of the manipulator.

Principal Adviser Robert Cannon **Ref. 1038**

BRUCE E. GARDNER

No. 3

Feedforward/Feedback Control Logic For Robust Target-Tracking

Feedforward compensation has for some time been recognised as a means for improving the ability of a control system to track the motions of a target. However, implementation requires target motion sensors, which may be costly. In addition, the control system is more complex and may be more sensitive to variations or uncertainties in the dynamic parameters of *both* plant and target. The question is thus raised as to whether a feedback-only control scheme can be designed that provides nearly as good performance with lower cost, less complexity, and reduced sensitivity.

The major objective of this research is to determine circumstances under which inclusion of feedforward compensation can be expected to offer enough performance gain to justify the costs of implementation. To this end, tracking error and control responses are analyzed and linear simulations are conducted to study the "zero-placement" mechanism by which feedforward and feedback compensation elements influence these responses in the presence of plant and target uncertainties. A quadratic performance index that allows separate weighting of transient and steady-state tracking criteria is formulated and incorporated into an algorithm ("SANDY1") for synthesis of low-order, robust, target-tracking controllers. Two design studies are conducted that focus on target-tracking for:

(1) Two-Link, Two-Actuator Mechanical Robot Arm

(2) Shipboard Recovery of a Remotely Piloted Vehicle (RPV)

The results indicate that, in important cases, feedforward can greatly enhance both transient and steady-state tracking characteristics in the presence of variability and/or uncertainty in the dynamic behavior of plant and target. Sensor noise is the limiting factor in the performance improvement attainable with feedforward. For higher sensor noise levels, significant improvements in tracking acccuracy with constraints on control effort can be realized with feedforward of target rate variables in addition to the position variables.

Principal Adviser Robert Cannon **Refs. 1036, 1059**

DAN E. ROSENTHAL

No. 2

Experiments in Control of Flexible Structures with Uncertain Parameters

Control requirements for large flexible space structures are difficult to meet in the presence of model uncertainty. The control system is particularly sensitive to spacecraft properties when the sensor and actuator used for control are separated by structural flexibility, i.e., they are noncolocated.

A laboratory structure has been built which incorporates several aspects of the problem posed by large space structures:

1. The laboratory system has extremely low damping ratios in the vibration modes.
2. The system is equipped with noncolocated sensor and actuator.
3. Some of the system parameters can be changed abruptly while the system is under closed-loop control.

The laboratory system provides a setting in which suitable control algorithms can be developed and tested, for providing control which is insensitive or 'robust' to plant model errors. Controllers have been synthesized using gradient search programs. Controllers of various orders were computed and are compared in this thesis. Experimental results will be presented which indicate the extent to which nominal performance must be traded off to achieve robustness. These results will also be compared to results that can be obtained using classical control theory and modern optimal control methods.

Principal Adviser Robert Cannon **Refs. 1032, 1034, 1039, 1062**

UY LOI LY

No. 1

A Design Algorithm for Robust Low-Order Controllers

Control-law synthesis for linear systems based on the optimization of the expected value of a steady-state quadratic performance index (linear-quadratic-Gaussian (LQG) synthesis) has been extensively used in multi-input multi-output systems. However the resulting controller is complex, the order is high, and it is sometimes quite sensitive to parameter variations and other modelling errors. In this research we have developed an efficient, reliable and robust design algorithm for the synthesis of optimal low-order controllers that are insensitive to plant parameter variations.

Previous algorithms for robust low-order controller design require an initial guess of the controller parameters that yields a stable closed-loop system. This requirement is eliminated here by the use of a finite-time quadratic performance index. The finite-time performance index and its gradients with respect to the unconstrained compensator gains are evaluated analytically, thereby speeding up the convergence of the nonlinear programming search. Design robustness is accomplished using an expected value of the performance index over the domain of parameter variations and unmodelled dynamics.

Applications of our algorithm are given for different optimal control problems such as optimal tracking and disturbance rejection, lateral and longitudinal aircraft stability augmentation systems, control of a flexible mechanical system with plant parameter variation, and control of an unstable open-loop plant.

Principal Adviser Robert Cannon **Refs. 1031, 1033, 1040**

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