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NAVAL POSTGRADUATE SCHOOL

Monterey, California

A Mechanical Predesign
Project in Robotic
Fire Fighting

by

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A four student design project was formed to investigate the design of a Navy robotic fire fighter. The project goals were centered around identifying appropriate Mechanical Engineering (ME) masters thesis topics while accomplishing a worthwhile engineering project. As an ME involvement, the project was approached as an exercise in machine preliminary design. A 16 week format was used with time equally distributed between background building and design. Lecture hours were minimized

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) (to nine) and one-on-one and group technical discussions were maximized. None of the students had prior background in robotics. Each student selected a task in robot design in which to become "expert". The four tasks investigated were: manipulator mechanism design; end effector design; motion control; and man/machine interfaces.

The students results are presented as submitted. Alternative engineering design concepts are discussed for each of the major system components. The evolution of system design requirements is discussed. A recommended system configuration is identified.

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I. Introduction

The new academic researcher to the field of robotics may be quickly overwhelmed by the proliferation of published material reporting on robotics research. According to the Dialog library reference service, the years 1977-1985 witnessed 5783 publications on a wide variety of topics relating to robotics. In order to manage this formidible data base, the researcher may try to organize it into fields of research further categorized into task-oriented topics. For example, in the present project, five machine design tasks were identified within three fields of investigation: mechanical engineering (manipulator mechanisms design, end-effector design, motion/force control strategy); electrical engineering (control data processing implementation and artificial intelligence (task planning). This organization of the literature is important in that it suggests a "natural" design project structure which associates each design team member with one or more design tasks. Such task-oriented project structures are widely and successfully used in the aerospace industry. The objective of this design project was to investigate the use of a task-oriented project structure in the academic environment to achieve specific educational and engineering goals.

In order to maintain student and faculty interest, a real Navy engineering project was identified for the student project focus. Several discussions with Mr. Russ Werneth at the Naval Robotics Lab, Naval Surface Weapons Center (NSWC), White Oak, MD, led us to concentrate on the Navy's Fire Fighter Project (NFFP). At the time, the NFFP was evaluating several first-generation, tethered, teleoperated vehicles for use in shipboard fire fighting. The project management was however, interested in possible ways that robotics could be implemented in the next generation of fire fighters. The student's engineering objective thus started out to be completion of the predesign of a robotic, add-on, high payload-to-weight manipulator to be used for foreign object debris (FOD) removal. The objective evolved into something different as will be discussed below. In support of the objective, the engineering goals for the student team were established:

- To define the system design requirements
- To identify candidate approaches to the design problem
- To select a system design concept
- To complete the predesign of major system components

The design team was composed of four graduate students and a faculty member. All students were working towards a masters degree in Mechanical Engineering (ME). One student had an above-average background in Electrical Engineering (for an ME) and elected to define and address the control problem. The students were mature, dedicated, and highly motivated; all were Naval officers with 6-12 years of experience. The faculty member had been teaching for about a year and had recently come from a project engineers job in the aerospace industry. None of the student team members had any significant background in robotics prior to the start of the project, all but one had taken a course in machine design. The faculty member had conducted a library search and had taken a one-week short course in robotics prior to advising the course.

The project educational goals were centered around identifying appropriate ME thesis work in the robotics area. As an ME involvement, the project was approached as an exercise in machine preliminary design. This gave the students an excellent exposure to a team design project and the difficulties associated with this type of work. It was hoped that they were thus better attuned to the organization and approach of similar industrial design projects. The educational goals are listed below:

- To prepare students to understand the robotics literature and engage in state-of-the-art design discussions.
- To identify and organize the robotics literature data base.
- To familiarize students with the team design process and especially the preliminary design process.
- To identify the necessary prerequisite courses and lecture content for a similar robot design course to be offered in the future.
- To identify the necessary additional coursework for follow-on thesis work in robotics.

II. Teaching Approach

The general approach was to minimize lecture hours and maximize one-on-one and group technical advising. Students were encouraged to take the initiative and deal directly with the sponsoring lab on questions regarding design objectives. Weekly progress reports were used to keep everyone up-to-date and to emphasize a system synthesis orientation. It was not clear at the outset where the lecture emphasis should be placed, so a wide range of topics was presented in an overview fashion. As the design effort proceeded, skills shortfalls were expected and were noted. The schedule consisted of a one hour lecture plus a one hour progress meeting per week for the first 9 weeks, followed by a one hour progress meeting per week for 4 weeks, and ended with a two week period without meetings for written reporting. The following topics were lectured for the first nine weeks:

1. General concepts and robot geometries
2. Open chain kinematics
3. Jacobians
4. Open chain dynamics
5. Trajectories and open chain control

6. Linkage design: degrees of freedom

7. 4 bar - function generation

8. 4 bar - path generation

9. 4 bar - motion generation

At the outset of the project, the students were encouraged to consider both open and closed chain linkages as manipulator configurations. The last four lectures were added in response to their request for additional background on closed chain mechanism design.

The first teaching issue to be addressed was the identification of good source material for lectures, homework, etc. The often used books by Coiffet and Chirouze (1) and Paul (2) make wonderful shelf references but are ill-suited to the classroom. As a first entry into this field, John Craig of Stanford has formalized his notes into an introductory text to be published soon (3). Craig's draft of text was used as a principle resource along with Sandor and Erdman's text on mechanism design (4).

III. Engineering Approach

The faculty project leader was responsible for the system synthesis. This ensured that component designs were consistent with each other and with the system engineering goals. The students each had an area in which to become "expert" through library research, lecture, homework, etc. The students were encouraged to do all of the designing. Figure 1 shows the engineering project structure. The figure shows the four design areas which were addressed by the four student design team members. As mentioned earlier, the students dealt directly with the lab on questions of project objectives while their principle source of technical guidance was at the NPS.

It should be emphasized that this project addressed predesign issues. That is, it identified design requirements and design concept alternatives.

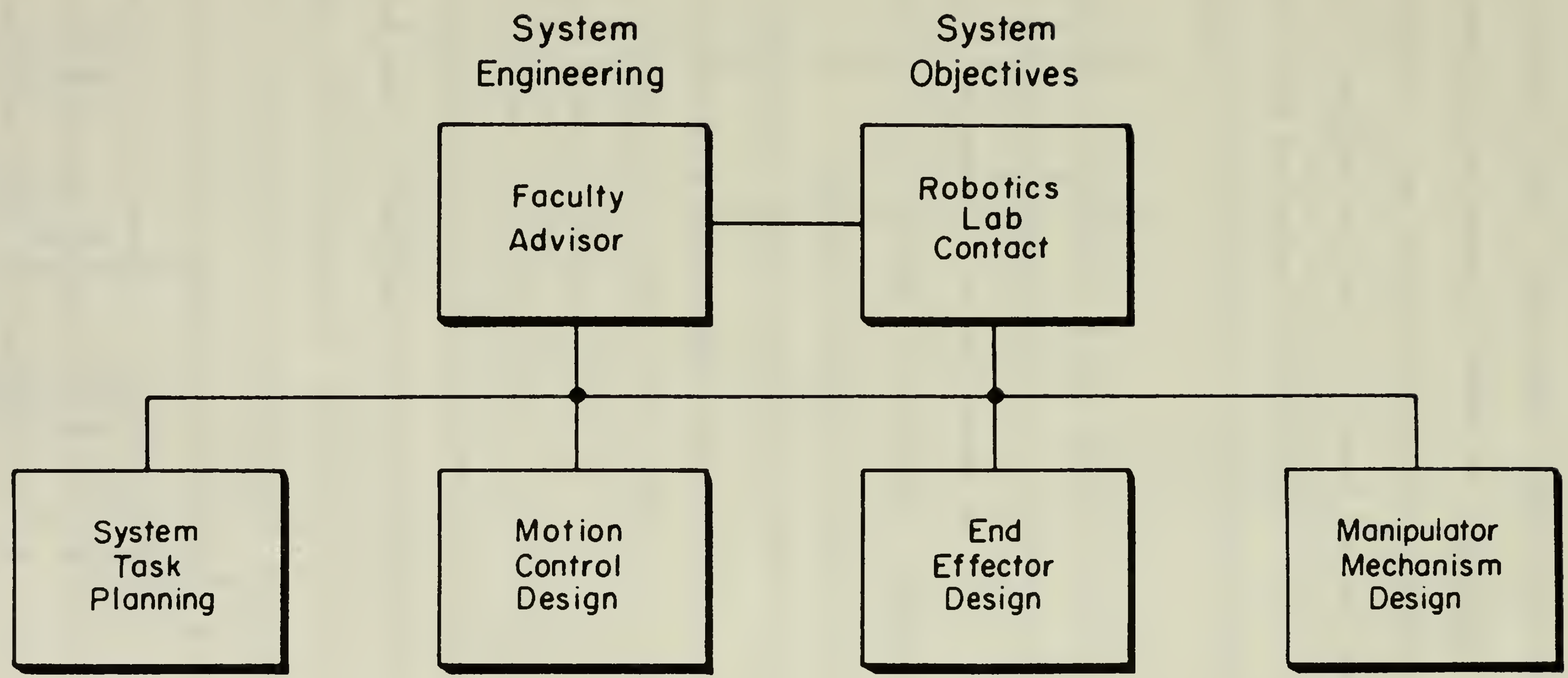


Figure 1. The Project Structure.

In general, a predesign stage of product development is followed by a design stage where detail design of parts takes place. This, in turn, is usually followed by prototyping, test, and redesign stages before manufacture. Consequently, the predesign work of this project was very concept oriented. Evaluation of alternatives was based only upon the briefest engineering analyses. It was hoped that this predesign background would form a logical departure point for detail design to be completed during subsequent thesis work.

The schedule of project work is shown in Figure 2. The figure shows that more than half the time (weeks 1-9) of the project was spent in learning basic material and in identifying the system design requirements. Simultaneously, the robot system integration (manipulator, vehicle, and man/machine interfaces) was being discussed in progress meetings.

The simultaneous development of system design requirements and system hardware concepts is a situation not often enjoyed in military procurement. The government Request For Proposal (RFP) process requires that the customer specify a minimal, firm list of design requirements towards which all bidders must respond. Underspecification of requirements may lead to confusion on what the customer wants, while overspecification leaves little room for design creativity. Most RFP's are somewhat underspecified in order to facilitate the predesign process and give the broadest range possible for concept development. It is usually not desirable to the contractor to repeat the RFP proccess as proposals are expensive to generate. However, it is advantageous to the customer to iterate on his design requirements as different requirements generally produce different designs, sometimes radically so. This is especially true at the 6.2 (exploratory development) level of research where new fundamental concepts are first being developed into hardware

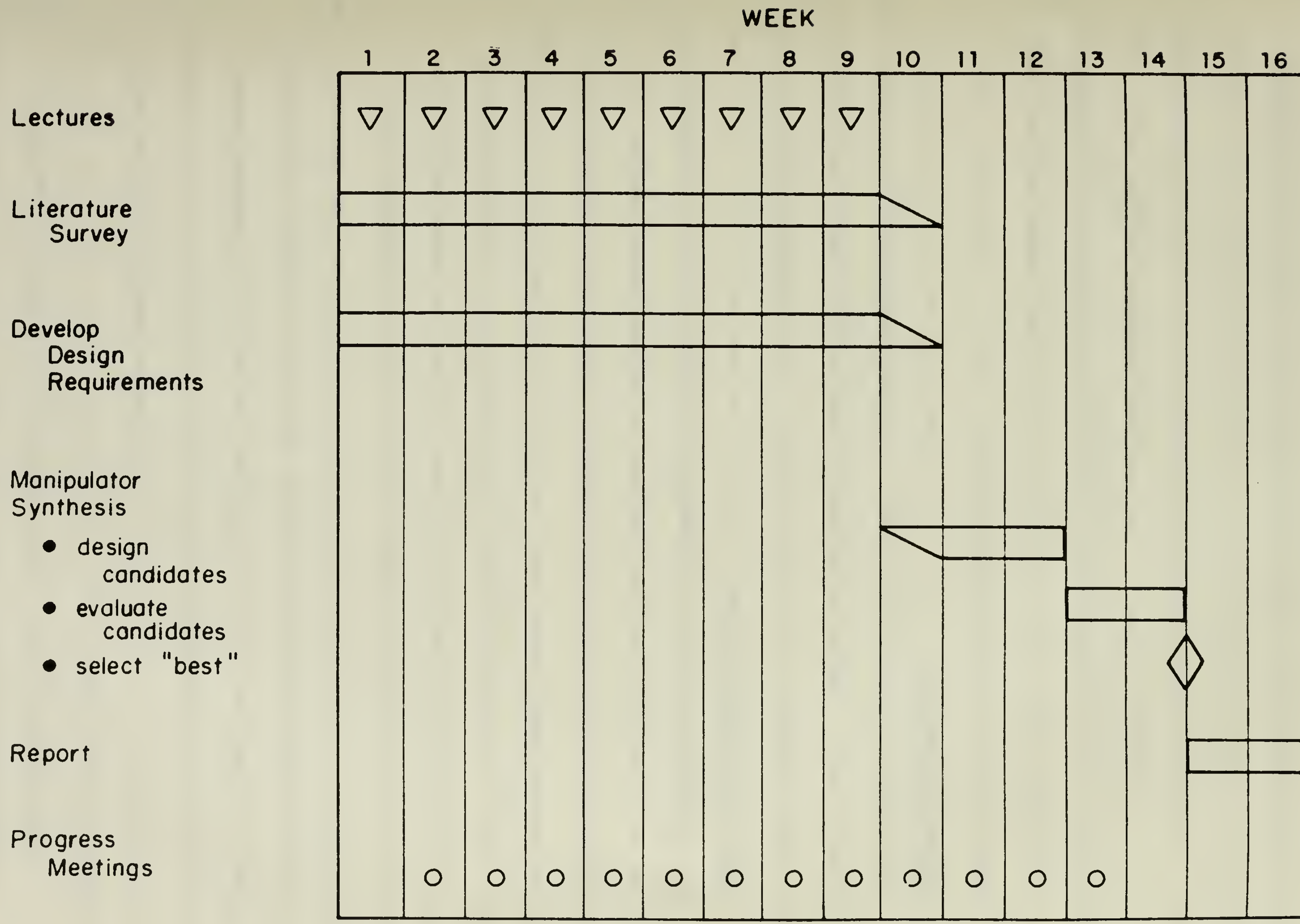


Figure 2. The Project Schedule

systems. The faculty at a school such as the NPS can benefit from doing predesign work with underspecified or ill-defined requirements since they can learn of the needs for new fundamental technologies in the process, they also get to meet a proposal customer. The students benefit since they participate interactively in the design process in the role of contractors. The students thus concurrently learn about the design process, learn about robotics, and meet those actively involved in the field.

IV. Engineering Results

This section of the report presents the engineering results in five categories of work: system design requirements, system operating concept, system control concepts, end effector design, and manipulator design.

A. System Design Requirements

The evolution of design requirements was one feature of this project which was both perplexing and productive. At the outset, an add-on manipulator was desired which could operate as a FOD removal tool with a payload-to-weight ratio arbitrarily set at 10. The possibility of a flexible (versus rigid) arm was discussed and the work was begun. After about six weeks, the robotics lab identified a potential need for an end-effector to pierce the surface of the burning aircraft in order to administer fire fighting agents to the interior of the craft. In this way, the fire was to be simultaneously fought from the inside as well as the outside of the burning structure. Towards the end of the project, the need for a general purpose system came to be understood since system idle time needs to be minimized and utility maximized. The final set of system requirements, listed in order of importance, are given below:

- Navigate a potentially rough terrain and position the vehicle for operations.

- Manipulate and direct a fire hose and nozzle to fight the exposed fire.
- Manipulate a structure piercing tool to fight the interior fire. This may require a second arm.
- Conduct FOD removal of bombs, debris, hoses, etc.
- Conduct CBR decontamination.
- Clean and maintain aircraft and ship surfaces.

The development of these requirements was a team effort achieved mostly through discussion at progress meetings. In the sections which follow, the students' individual contributions are presented.

B. Man/Machine Interfaces

The focus of this system evaluation is the interface between the robot and a human monitor/operator. Several assumptions on system constraints were made to clarify operational details as follows:

- Operations were to be restricted to the aircraft carrier flight deck, or land base operations, and not carry over to fire suppression on a hangar deck or in other compartments within a ship.
- Fire fighting water (seawater) was to be obtained from the ship's firemain system rather than carried onboard the vehicle.
- The robot was not to be totally autonomous. Some form of interactive robotics was desired with remote operator guidance to manage task planning in real time. This was determined to be necessary for gross positioning, while the robot would manage its own fine positioning control in the smoky environment.

Following the operational requirements and system constraints discussed above, an operational scenario was developed. Each specific phase of deployment was analyzed for its constituent elements and hardware or sensor dependency. To address both ends of the complexity scale, two methods of navigation were considered. One, at the present state of industrial application, consists of a teleoperator device and an operator stationed at some vantage point. The other system involves an encoded deck and a sensor/navigation processor onboard the vehicle, operator control is exerted by destination-point designation to the processor (map-mouse system), and the robot has a higher level of autonomy. The distinct phases of the scenario are analyzed below.

1. Stowed Position: vehicle ready for flight operations; the vehicle is spotted; tiedowns removed; expendables topped off; weekly performance check OK; fire hose connected.
2. Machine Start: signal received from operator station; vehicle propulsion starts; vehicle moves away from spot; systems pressurized; unreel tail cable and/or fire hose.
3. Vehicle Navigation: Steering control system manipulates wheels to maneuver vehicle.

    (a) Map-mouse system with onboard processor and grid sensor: operator indicates vehicle destination; operator indicates avoidance areas; onboard sensor determines vehicle position from encoded flight deck; onboard navigation computer plots course and generates signals for steering control systems.

    (b) Tele-operation from operator station: operator observes vehicle destination; operator observes avoidance areas; operator observes present vehicle location; operator sends signals for steering control.

The vehicle destination is a burning aircraft. Avoidance areas include spotted aircraft, loose ordnance, debris, and deck areas afire from fuel spills. Flight deck encoding may be electronic, magnetic, visual, or acoustic, with a grid of various possible mesh sizes. At minimum, three nodes under vehicle footprint are required to provide positive orientation. Visual encoding on flight deck surface may be obscured by foam or fire damage.

In the tele-operator system the operator's visual contact with machine is required to achieve a closed loop control, smoke from the fire may prevent this.

4. External Fire Proximity Enroute: commence sweeping spray of Aqueous Fire Fighting Foam (AFFF) and/or water coolant.

   (a) Map-mouse system: signal received from onboard thermal sensor.

   (b) Tele-operator system: operator observes flame proximity.

Thermal sensor indicates temperature is in excess of design parameter and initiates egress planning and coolant ejection. Coolant application continues until the temperature is safe or override signal is received to continue/retreat.

5. Aircraft Proximity: vehicle traverses course which terminates in acceptable spatial orientation to aircraft; angular parameter is normal to long axis; distance parameter is 8-10 feet from fuselage.

   (a) Map-mouse system: Operator indicates orientation as part of destination at outset. Alternatively, onboard sensors seek aircraft as specified destination is approached.

   (b) Tele-operator system: Operator observes aircraft orientation and adjusts steering signals to obtain desired path.

Operator specification of orientation at outset requires more sensitive control pad at operator station, also more operator training. Final positioning may require combination of sensors. Onboard sensor detection of aircraft orientation requires a sensor range of 20-30 feet. An acoustic sensor is preferred to radar due to hazard to ordnance, but this adds complexity to the vehicle. A signal from operator station presumes clear vision again and provides override in event of failure of sensor or grid-oriented system.

6. Destination Achieved: vehicle propulsion disengaged; brakes applied; stabilizers extended if present.
    (a) Map-mouse system: sensed location compared to ordered destination.
    (b) Teleoperator system: Operator observes vehicle destination to be as desired.

An end-of-sequence signal triggers the start of robotic arm control which is discussed elsewhere. Continued monitoring of vehicle position and orientation is used to determine if the vehicle/aircraft is slipping. A position change causes arm system balk and initiates retraction unless override directs otherwise.

7. Extinguishing Agent Applied: fire fighting is conducted and completed; trajectory calculated to stowed position; actuator signals generated for arm control system; actuators position arm in stowed position.
8. Vehicle Retraction: Vehicle traverses flight deck from deployed position to ready spot.
    (a) Map-mouse: Onboard navigation processor plots "reciprocal" course, generates signals for steering control system.
    (b) Tele-operator system: Operator observes destination, avoidance areas, present vehicle location. Operator sends signals to steering control system.

9. Stowed Position: Vehicle returns to starting station.

C. Motion Control

In order to develop robot internal control implementation concepts, a set of control design goals was identified. These goals were regarded as the minimum set. No attempt was made to identify a specific worst case scenario, although unfavorable situations were considered. The following system design goals were identified:

A. Provide control signals for the robot to guide its operation from stowage prior to a fire, through the steps necessary to combat the fire to extinguishment, and return of the robot to stowage.

B. Provide sufficient sensor and data feedback to a human operator to allow for remote human operator monitoring, decision making assistance, and/or direct control.

C. Accomplish above as rapidly as necessary to reduce material and economic loss due to fire and to prevent human injury.

D. Design the system to be user friendly and simple enough to be operated by average E-4 Sailors.

E. Include a training mode to provide hands-on operator training.

Given the control system design goals as outlined above, the operational scenerio was reviewed to determine more precise controls requirements. The basic system investigated was the map-mouse system discussed previously. Twelve distinct sequences of operation were identified for the fire fighting mission. The reader should note that this control sequence evaluation is aimed at identifying robot autonomous task requirements compared with the previous system evaluation which investigated human/robot interfaces.

1. Navigate: Provide platform movement control for gross motion from alert area to the vicinity of the aircraft fire.

2. Initial Approach: Provide movement control for finer positioning of platform to attack fire. Includes sensing of fire and deployment of some agents for self-protection, possibly from onboard stocks.

3. Deploy Arm: Provide motion control of articulated arm to make it ready it for use and to bring its sensors into play.

4. Final Approach: Provide coordinated motion control for both platform and arm to achieve optimum geometry for initial deployment of fire fighting agent and/or contact with the burning structure.

5. Structure Contact: Provide motion control of arm and end effector to initial contact with structure and evaluation of quality of contact position.

6. Adjust Contact: Upon sensing and evaluating initial effector contact provide coordinated motion control of both platform and arm for adjustment of effector to optimum contact orientation.

7. Enter Structure: Provide control of the arm and end effector to achieve penetration through the exterior of the burning structure and attachment of the end effector to the structure. Penetration can be:

   a. through existing hole
   b. drilled
   c. punctured
   d. blasted
   e. sawed

8. Evaluate Entry: Provide quantitative measure of:

a. penetration depth

b. proximity to seat of fire

c. probability of success of extinguishing attempt at this position.

If not satisfactory, withdraw and go to sequence 4 to try again, or query operator.

9. Apply agent: Provide control of fire fighting agent application to include:

a. determination of optimum agent (can be mode dependent, i.e., put out fire, cool ordnance, save life).

b. pressure/volume/quantity of agent to be applied, which include backpressure sensing to determine if flow restriction exists.

c. fire out detection and application cutoff.

10. Withdraw: Provide control of detachment and withdrawal of end effector. Attempt to avoid damage to effector in two modes:

a. normal withdrawal

b. emergency (abort)

11. Restow Arm: Provide control of arm to return it to stowed position.

12. Retreat: Provide control of platform navigation to retreat from scene.

NOTE: Sequences 2 through 5 need not occur discretely. They may be simultaneous and coordinated. Likewise, sequences 5-7 may be coordinated if penetration occurs through an existing hole.

During the execution of all phases of the above sequences, a minumum set of supervisory self protection functions must be performed. These include sensors and actions to detect and compensate for:

a. Heat: apply self-protective water spray, cool internal electronics with compact heat exchanger.

b. Blast: put down skid pads, augment brakes.

c. Wind/Deck roll: put down skid pads.

d. Obstructions/Holes in deck: visually or acoustically scan deck to refine navigation control.

e. Overstress of individual components: visually or otherwise scan working environment to predict/avoid obstacles which could fall on arm. Strain gages can be used on weakest links to detect overstress and enable response by adjusting configuration to reduce stress.

Concurrent with the safety features, operator data feedback must also be continuously provided to assist in real-time human monitoring, decision making, and intervention. The fedback sensory data should include but not be limited to:

a. Visual: both external gross remote television and views from interior of burning structure could be provided via fiber optics included in penetrator part of end effector.

b. Thermal: radiated heat, surface temperature of structure, and internal temperature of robot can be provided.

c. Ambient: presence of oxygen, poison or explosive gases, explosive compounds (HE, etc.), and nuclear fissionable materials should be provided.

The investigation of a control design for the above sequences has led to the following set of possible strategies and sensor applications. The strategies and their implementation are presented for each sequence step. In cases where more than one strategy or implementation is suggested, each strategy is presented under the appropriate sequence step.

1. Navigate

a. Strategy: Minimum time, obstacle avoidance.

b. Implementation: Path control, initial path determined by location of major obstacles (parked aircraft, yellow gear, deck structures, etc.) which can be input to robot controls before detachment of umbilical from ships flight deck management and status system via data bus, or directly input via keyboard, touch sensitive pad, or touch sensitive CRT screen. Refined path determined by onboard sensors and controls to avoid unexpected obstacles or dangerous environments (moved aircraft, damaged deck, etc.).

c. Sensors: Visual, proximity, tactile, thermal for obstacle and fire detection and telemetry to human operator. Telemetry may be accomplished by RF, hard wire or fiber optic link. Visual, radar, tactile or magnetic (coordinate grid installed in deck) for self-location.

d. Risks: Human operator may intervene prematurely. Self-location ability may be lost (damage to deck grid, obscured vision, loss of radar reference points). Damage from unforseen event (bomb blast, collision with moving object (aircraft, bomb dolly, etc.).

2. Initial Approach

a. Strategy: Minimum time, obstacle avoidance, optimum final position.

b. Implementation: Path control, accomplished by direct evaluation of onb sensor information to approach burning struc re from best direction to extinguish fire (upwind, offset, nearly perpendicular to axis of structure). The point of attack can be the initially hottest spot.

c. Sensors: Vision, proximity, thermal, tactile as above.

d. Risks: Same as above.

3. Deploy Arm

a. Strategy: Minimum time.

b. Implementation: Path control.

c. Sensors: Same as above with addition of articulated arm joint position and velocity sensors, and additional visual, proximity and thermal sensors in end effector (proximity and ranging sensors on end effector must be precise to be useful in the final positioning sequence) the sensors on the end effector become primary telemetry sensors once unstowed.

d. Risks: Same as above.

4. Fi al Approach

a. Strategy: Minimum time.

b. Implementation: Path control, accomplished by controlling both the articulated arm and mobile platform motion, using information from both platform and end effector sensors to achieve best location and orientation for fire extinguishment. This may be initial position for penetrating the structure, or best vantage for external application of extinguishing agent. The plan of attack will be determined by onboard algorithm or by human selection of external/internal mode during approach sequence.

c. Sensors: Same as above.

d. Risks: Obscured end effector sensors, broken telemetry/remote control link, failed processor, coupling of degrees freedom between platform and arm may require difficult, time consuming calculations.

5. Structure Contact

a. Strategy: Zero overshoot (don't want to contact structure with excessive force).

b. Implementation: Position control, accomplished by arm motion only, using arm position and effector sensors to simplify the fine control problem.

c. Sensors: Same as above, with addition of tactile force sensing for contact with surface.

d. Risks: Overshoot resulting in contact of structure with sufficient force (velocity) to damage effector or part of arm.

6. Adjust Contact

a. Strategy: Minimum time.

b. Implementation: Path control, accomplished by moving effector along surface of structure to locate best position for penetration. Chosen position must offer high likelihood of fire seat proximity and high likelihood of structure penetration. For example, if initial contact position lies on a stiffener, bulkhead, weld, or seam, a better position should be found.

c. Sensors: Magnetic, tactile, or visual to determine likelihood of penetration (can rely on physical characteristics of structure, or surface can be encoded to identify access points). Thermal to locate the seat of fire (find hottest point on surface).

d. Risks: Unable to locate likely point of penetration near hottest point, structure shifts due to effect of wind, sea, or fire, surface coding scheme damaged by high temperature.

7. Enter Structure

   a. Strategy: Minimum time, force controls

   b. Implementation: Control of this sequence step is strongly dependent on design of penetrator, and can be very complicated.

   c. Sensors: Tactile and others necessary to operate penetrator.

   d. Risks: Structure resists penetration

8. Evaluate Entry

   a. Strategy: Enable injection operations.

   b. Implementation: Direct measurement of depth of penetration, infrared spectrum, and interior temperature. Telemetry of visual information from interior of structure to human operator for additional evaluation and overrides.

   c. Sensors: Direct distance measurement, thermal, infrared spectroscopy, fiber optic visual probe.

   d. Risks: Sensors or penetrating portion of effector damaged by fire or by movement of structure. Not at location of fire.

9. Apply Agent

   a. Strategy: Position/orientation servomechanism.

   b. Implementation: Apply quantity and type of agent determined most likely to succeed by internal logic and sensor information or by human decision-maker and remote link. Monitor parameters during application to determine desired rate and location (can be accomplished by combination of flow rate and visual/thermal sensors).

   c. Sensors: Same as above plus agent volumetric flow rate

   d. Risks: Amount of agent chosen to be delivered is too little or too great. If too little, the situation it can be easily remedied by detection of residual fire and re-application of agent. If too much agent is applied, both time and extinguishing agent are wasted. This can be remedied by inclusion of an algorithm to detect the fire-out condition.

10. Withdrawal

a. Strategy: 1) Normal mode: Obstacle avoidance

2) Energency mode: Minimum time.

b. Implementation: Reverse of penetration process. Normal mode withdrawal may be initiated by failure of successful penetration evaluation. In emergency mode (initiated by human operator overide or detection of overstress in arm from collision with collapsing structure) detach end effector traumatically from structure possibly by removal of all or part of end effector from arm.

c. Sensors: Same as above

d. Risks: If part of device is lost in this sequence, robot may be unable to be reused without repair.

11. Restow Arm

a. Strategy: Obstacle avoidance.

b. Implementation: Path control, accomplished by reversal of deploy procedure.

c. Sensors: Same as deploy

d. Risks: Same as deploy, plus if robot damaged during withdrawal restow may not be possible.

12. Retreat

a. Strategy: 1) Normal mode: Obstacle avoidance

2) Emergency mode: Minimum time.

b. Implementation: In normal mode, path control to retrace path taken during approach to avoid damage to umbilical and fire hose (requires human assistance to retrieve umbilical and hose or second arm control). In emergency mode, path control may be used to remove robot from the vicinity of the burning structure without regard for minor damage to the umbilical. Although the robot must avoid collision with any major structures, it can avoid major damage to the hose and umbilical by jettisoning them as part of the emergency retreat.

c. Sensors: Same as approach sequence.

d. Risks: Damage to umbilical and subsequent loss of human override capability.

D. End Effector Design

The design of a gripper/controller for a fire hose nozzle was seen to be a straight-forward task and was not pursued in favor of doing the predesign of the penetrator end effector. As currently envisioned, the end effector must perform five primary tasks:

A. Final, positioning of the penetrator.

B. Attachment to the airframe.

C. Penetraton of the airframe.

D. Final control of pumping fire fighting agent into the airplane.

E. Detachment for further use.

In the positioning task (as opposed to most industrial robotic applications), precise, repeatable end effector positioning is not required. However, it is still necessary to safely and expeditiously orient the penetrating device to the aircraft skin to ensure proper penetration of the aircraft, and to provide proper seating during agent injection.

During attachment, the goal is to provide a method to counteract the forces, moments, and torques required in the next steps of penetration and pumping.

Previous research on penetration has led to a manually operated (i.e., hand-held by a human fire fighter) penetrator which utilizes a pneumatic drill to penetrate the aluminum aircraft skin, wiring harnesses, acoustical insulation material, and cabin panels of a C5A, resulting in a penetration of 14 inches (5). Although this figure corresponds to a far larger plane than would be found on an aircraft carrier, it is felt that the difficulties of design based on this "worst case" of 14 inches would be a worthwhile design goal. This provides a difficult and restrictive design problem through greater weight and power requirements. The penalties would, however, be offset by design universality, the same robot used on the USS Kitty Hawk could be used at Miramar Naval Air Station.

The end effector must supply a final control gate to the pumping of AFFF into the airplane. It must be capable of handling the high pressures and flow rates of AFFF found on an aircraft carrier; i.e., 100 psi and 200 gpm. The use of Halon as an interior fire extinguishing agent was also considered. Two cases of pumping stoppage must be considered: when the fire is extinguished and when an emergency arises. The former case involves a sensing device capable of determining the status of the fire, particularly when the fire is out. The latter case involves sensing when some abnormality exists in the operation. For example, if the end effector somehow worked loose from the aircraft, a motion-detector could enable an order to stop pumping.

Upon extinguishing a fire, the robot should be capable of detaching from the aircraft and proceeding to a new fire without delay or difficulty.

Following the outline of end effector operational tasks discussed above, the penetrator hardware concepts were identified. Five concepts for penetration were examined as discussed below. The concepts evaluated were pneumatic drilling, water powered drilling, electric drilling, "brute force penetration", and laser cutting. A sixth concept, water jet cutting, was added at the end of the project, too late for detailed evaluation. It is included in the interest of completeness.

1. Pneumatic Drill

This method of penetration was selected by the Robotics Lab as the most viable option for near-term use. As mentioned previously, the U.S. Air Force has already developed a hand-held penetrator of this variety, and operational tests to date have been satisfactory (5). Although this unit uses Halon as the extinguishing agent, only minor modifications would be required to allow additional use of AFFF; (the drill would require enlargement). The weight of the unit is 22.3 lbs. which includes a charged air flask. In the current proposal, it is recommended that the air flask be carried on the robot platform, and a hose assembly be run to the end effector.

2. Water Operated Drill

Although no current models of a water operated drill are believed to exist, several distinct advantages over other drilling methods justify further study and possible design in this area. These include:

1) Possible weight reduction through the use of a lightweight turbine bucket.

2) Less complexity - no external power source.

3) No limit on the number of holes that could be drilled.

3. Electric Drill

There are several disadvantages involved in the use of an electric drill (i.e., more weight and susceptibility to water damage) but the major reason for rejecting this option is the difficulty of providing the necessary electric power. Even though the robot will not be self-contained in the sense that it will be dragging the fire hose behind it, it is recommended that electrical cords not be dragged due to their high susceptibility to damage in the projected hazardous environment. Of course, batteries could be placed on the cart to power the drill, but it is believed that this option would be heavier and less reliable than the pneumatic drill, and perhaps present a hazardous fume problem.

4. "Brute force" method

Various proposals along these lines were discussed in class, for example, the use of some type of shaped charge to effect penetration. This was rejected based on the difficulites of use in the hazardous environment of a fire. Several other methods, including hammer actuation, ram pressure, and the use of a cocked-spring, harpoon-type apparatus were discussed and ultimately rejected by other researchers (5). In general, prototypes of this latter type of device were hand-operated and rejected because human strength was not capable of providing the required energy for penetration. In the case of the harpoon, rejection was due to severe recoil characteristics and also because "anti-recoil features could be designed, but not within the limitations of a low-cost, high reliability tool" (5).

It is believed that the objections raised to the "brute force" method due to human factors criteria would carry over into robotic design, but more research effort in this area is required before a definite rejection is given.

5. Laser Drilling and/or Cutting

Although only a somewhat cursory look was given to this topic, common sense and good engineering judgment led to rejection of this proposal. Lasers have been linked to robots, but only in large industrial applications.

It was found that many of the advantages of a laser do not apply to this project. For example, the ability of lasers to drill small holes in difficult materials such as ceramics, or the fact that lasers need not contact the item to be drilled don't seem to be advantages in the present case. The specific disadvantages of laser do, however, apply; these include high initial cost, large size, and limited depth of penetration.

6. Water Jet Cutting

The application of water jets to cutting processes is not uncommon to industry. Given a boost pump system to achieve proper pressures, this may prove to be an effective way to penetrate aircraft materials.

The various types of penetrator concepts are shown in ranked order in Table I. For the near term, the best design option is modification of the Air Force Skin penetrator for Navy NFFP use. The top three concepts all have high effectiveness and low maintenance features, but the pneumatic drill concept is the only one with a low risk feature. Given some development time, either the water powered drill or water jet concept may prove to be very attractive in the NFFP application.

E. Manipulator Mechanism Design

The fire fighter robot will probably have two manipulators: one will manipulate a fire hose and nozzle to fight exposed fires, and one will manipulate an end effector/penetrator to extinguish interior fires. This section of the report presents a predesign of the latter.

The function of the penetrator manipulator is twofold. First, it supports a specially designed penetrator for use in piercing an aircraft fuselage and for dispensing a fire fighting agent. Second, the manipulator structure supports a firefighting hose or is hollow to transport the fire fighting agent. In reality, the connection of the effector to the

Table I. Evaluation of Penetrator Concepts.

Concept	Source	Cost	Effectiveness	Maintenance	Weight	Risk +
Pneumatic Drill	Compressed Air	Low	High	Low	Low	Low
Water Drill	Pressurized Water	Mod.	High	Low	V. Low	High
Electric Drill	Batteries, Umbilical	Low	High	Low	Mod.	Low
"Brute Force"	Springs, Compressed Air	Low	Mod.	Low	Mod.	Mod.
Laser	Umbilical	High	Mod.	High	High	High

+ How easy to apply, off-the-shelf, etc.

aircraft creates a closed-chain linkage structure which includes the aircraft fuselage as well as the robot. However, for the purposes of worst case design, it was assumed that the end effector is unsupported by anything but the manipulator which is subjected to weight and fluid dynamic load forces.

A five degree of freedom (DOF) manipulator was considered adequate for positioning the end effector. These five DOF included two planar positions, a rotation about the base, and pitch and yaw of the end effector (e.g. roll at the end effector was not needed). It was felt that the mobility of the fire fighting platform could provide the necessary adjustments to meet requirements for positioning the base rotation of the end effector. The out-of-plane yaw effects have been disregarded. These assumptions allowed for a simplification to a planar analysis of the manipulator. The three required planar degrees of freedom were thus 2 positions (x, y) and one orientation (pitch) for the end effector.

During the predesign stage, the length of each manipulator link was arbitrary but the overall reach of the manipulator arm was to be approximately 12.5 feet. This length of arm reach was determined after inputs were received from the Navy. The NSWC recommended perpendicular distance from the mobile robot support platform to the aircraft and the Naval Safety Center recommended the optimum vertical end effector penetration location, these geometrical dimensions are sketched in Figure 3. The length of the penetrator end effector was taken to be 1.5 feet which is slightly longer than the Air Force penetrator. The weight of each link, except the end effector, was assumed to be 50 pounds which was an estimate of a one inch diameter steel pipe of average link length. The weight of the penetrator end effector was taken to be 22.3 pounds based on the weight of the Air Force penetrator. The flow rate of the AFFF/water was assumed to be 250 gpm, while that of liquid

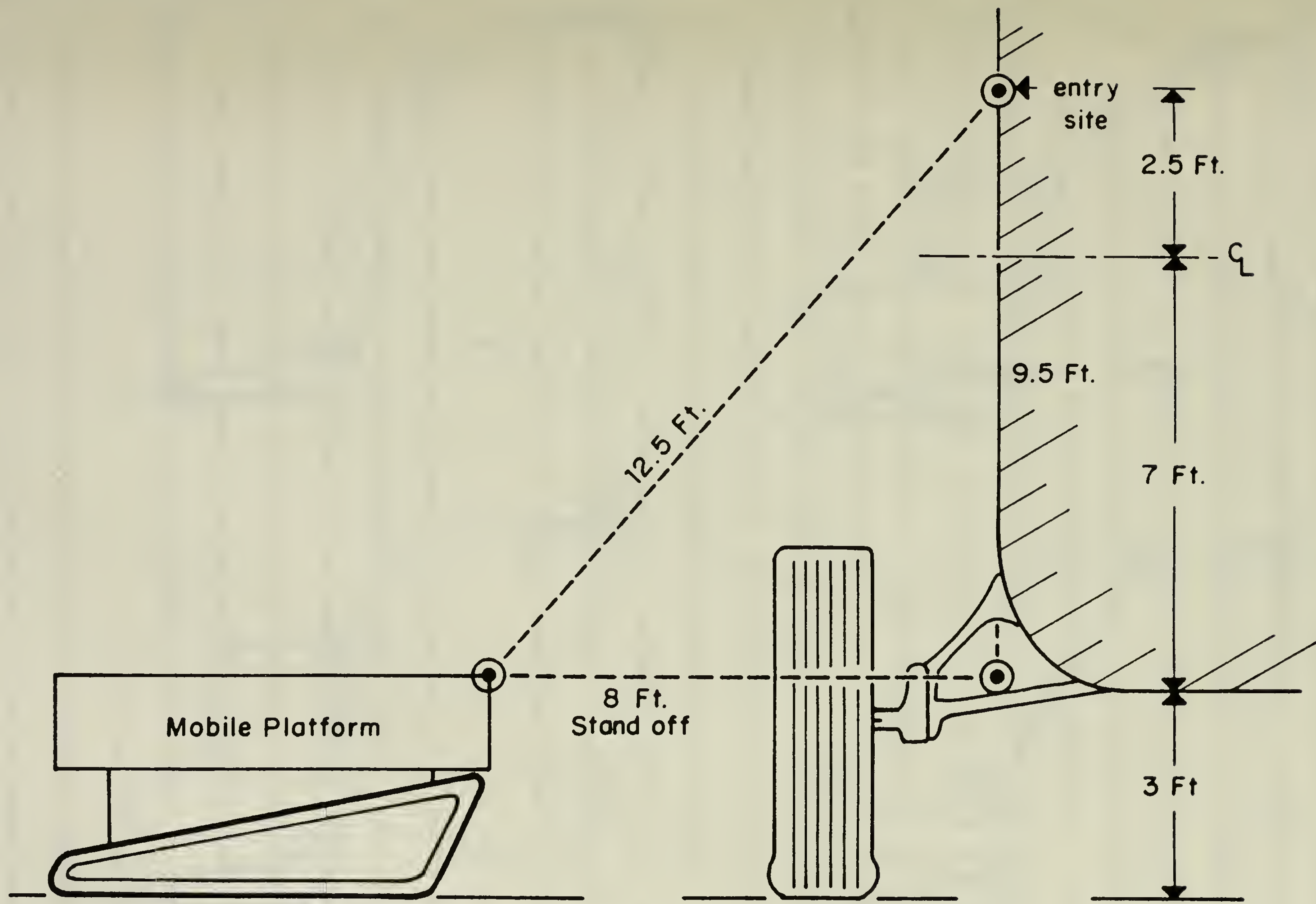


Figure 3. Worst Case Geometrical Requirement.

Halon was 20 gpm. The 20 gpm flow r for Halon was based on a five lbm/sec mass flow rate which is typical for on discharge systems (5).

It was decided to utililze some combination of an open chain with a four-bar mechanism for the manipulator structural candidates since these provide for relatively simple designs. A simple, open chain, three link mechanism was selected as a candidate since it has minimal moving parts (Design 1). A four-bar mechanism was chosen as an alternate base link structure because of its ability to distribute the applied loads compared to a single li , at the expens f structural complexity. Three designs using a four-bar e link were examined, two had fixed link l gths arrange in a parallelog m, while one had variable link lengths. One design had the fixed length four-bar base link with two additional open chain lengths to provide the necessary three DOF (Design 2). A second design had the fixed length four-bar base link with three additional open chain lengths (Design 3). In this case, the third, redundant link was added to provide a means to avoid control singularities. A variable geometry four-bar mechanism without add links was the fourth candidate (Design 4). The four designs are shown in Figure 4.

The criteria for evaluating the design candidates was their load carrying ability. Since joint load moments must be reacted by actuators, it seems clear that smaller moments require smaller actuators which, in turn, implies lower vehicle weight. The evaluation problem then is to find the geometric position of a given manipulator which gives the maximum joint torque, and to compare the maximum of each candidate with the others in order to select the most desireable.

A computer analysis of each proposed design was conducted to determine the maximum moment at each joint caused by the fluid forces and the weights of

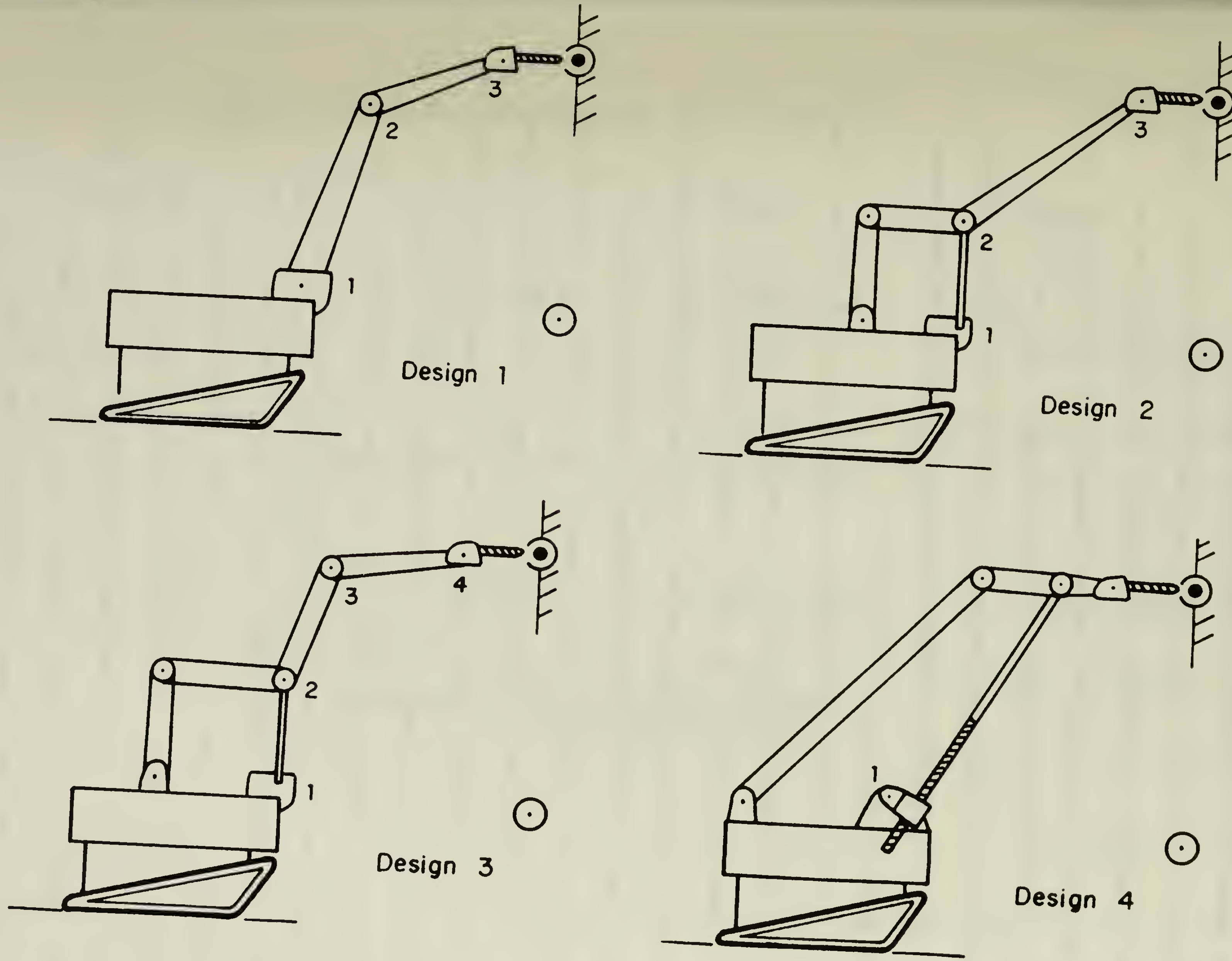
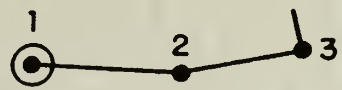
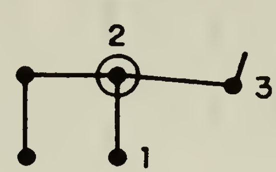
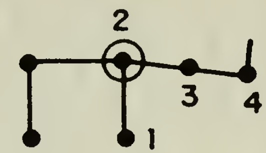


Figure 4. The Manipulator Design Candidates.

the links for a range of joint angles. In order to conduct this computer analysis, some assumptions needed to be made. First, the pipe inside or hose diameter was fixed at one inch, a size which was compatible with the Air Force penetrator end effector. The pressure of AFFF/water was assumed to be a constant 100 psi while the Halon pressure was assumed constant at 400 psi. The density of the AFFF/water was assumed to be that of water, 62.4 lbm/cubic foot. The density of the Halon was assumed to be that of liquid Halon (1301), 112 lbm/cubic foot. It was also assumed that the Halon did not vaporize over the relatively short length of manipulator arm.

The maximum joint moments were found by a brute force search method. The joint angles for each mechanism were typically sampled at 20 degree increments; although for design 3, 30 degree increments were sampled. As mentioned earlier, the analysis was considered as worst case since the joint moment arising from the fluid forces and the link weights were evaluated without considering the benefit of the support to the manipulator provided by the aircraft. The assumption of maintaining a constant line pressure of Halon or AFFF/water would technically only apply upon the initial activation of the fire fighting agent. After the initial activation there would be a drop in line pressure with a consequent reduction in joint forces and moments. The worst case moments and the corresponding configurations are shown in Table II. The tabulated data reveals joint moments resulting from the flow of Halon which were typically 1.5 times as high as the joint moments resulting from the flow of AFFF/water. As may be expected, the four-bar with variable length links (Design 4) resulted in the maximum joint moment about the base with the links in full extension. The three link open chain mechanism (Design 1) appears to result in the next highest joint moment. The four-bar with two additional links mechanism (Design 2) resulted in the lowest joint moment,

Table II. Evaluation of Maximum Joint Moments.

Design 1	Design 2	Design 3	Design 4
			
	MAXIMUM WATER PUMPING MOMENT ($Ft - lb_f$)		
j1/2828	j2/1636	j2/1840	j1/4046
	MAXIMUM HALON PUMPING MOMENT ($Ft - lb_f$)		
j1/4200	j2/2509	j2/2725	j1/5990

although the moments resulting from the four-bar with three additional links (Design 3) is not much greater. The advantage of having three additional links on the four-bar vice two additional links is that three links provide greater flexibility for positioning the end effector. However, the third additional link does not provide any additional DOF, so that a cost of the greater control flexibility is increased joint moments.

The recommended manipulator configuration is thus Design 2, a four-bar base link plus one additional link. If control singularities become a problem, Design 3 should be further investigated.

V. Conclusions

The students at the Naval Postgraduate School are not typical graduate students. They brought to this project a significant background in Navy fire fighting methods. They showed that they were capable of system and component predesign evaluations with little coaching in technique. The maturity, judgement, and experience they demonstrated are not typical of Master of Science students and it was these factors which helped to make the project an educational and engineering success. Also important was the willingness and availability of the faculty advisor to commit a disproportionately large amount of time to discussion sessions. For this reason, it was well that the student team was small. The amount of work was roughly equal to that of a 3 hour course for the students. More students would require more work from the faculty member in the present approach.

All of the educational goals were achieved. The students became familiar with the robotics literature and were able to engage in effective state-of-the-art design discussions between themselves and researchers from other campuses and labs. A brief series of robotics lectures seems to have been adequate preparation for the NPS students for this predesign, concept-oriented project. The students required no previous graduate coursework or special robotics background. A sixteen week format seems to be about the proper length for the project. This was clearly too much work for one academic quarter (11 weeks), but about right for a one semester course. Perhaps the most useful educational result was the identification of follow-on thesis topics for the student team members. As a result of this work, the students and advisor were well prepared to identify the thesis problems and the necessary additional preparatory coursework. There remains a clear need for a text to address robotics from a machine design viewpoint, complete with basic tradeoffs and options for design.

While this was primarily an educational project aimed at familiarizing students with engineering predesign, several important engineering observations came to light. The most important of these centered around a definition of the most effective way to fight a fire. Presumably, a stand-off capability is no longer needed with robotics, but many fire fighting methods and tools are designed to be used by humans which require such a capability. A question arises: if the robot fire fighter is made essentially invulnerable, could it then do a better job at the fire fighting task? Clearly, fundamental knowledge of how a fire behaves would help to guide and improve our efforts to fight it. Perhaps we may even eliminate the present hose and tether by more efficient use of fire fighting resources and using improved fire fighting tactics.

An advantage of robotics which has scarcely been examined is the exploitation of adjustable geometry. For a robot such as the present one, a high strength-to-weight ratio may be desirable for the secondary FOD removal task. Therefore, we may ask: given a certain actuator set, do various strength and speed task requirements imply different configurations (i.e., link lengths)? It seems that a robot can be made smart enough to evaluate this requirement and to adjust its geometry to meet the task. In this way, a robot can make best use of its available actuator power by adjusting its geometry. One such concept was briefly examined in this report (Design 4), it did not compare favorably with other concepts in light of the primary mission of the robot. However, it may be desirable to utilize this capability as an added feature which is always used, but achieves its biggest contribution to power saving during the FOD removal task. More fundamental work needs to be done on adjustable geometry for robotics.

As a final observation, it is important to recall that this design work was done on a two dimensional, planar mechanism. This was achieved by assuming that the robot could always approach the aircraft so that the manipulator plane is perpendicular to the drilling surface. In reality, the out-of-plane forces on the mechanism may be significant due to an oblique approach angle with oblique drilling forces, loss of hold on the aircraft, fluid flow forces, shifting aircraft parts, or any of a variety of other causes. More predesign work is required to define the problems associated with out-of-plane forces and to identify design concepts for accomodating them.

In the course of this predesign work we rediscovered that machine tasks must be well defined before the machine can be designed in detail. Our goal was not simply to replace the human fire fighter, but to design a machine that takes advantage of robotics to more effectively fight a fire. A task-oriented approach to this design problem has proved to be effective in accomplishing both educational and engineering goals.

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