A Systems-Level Modular Design Approach to Field Robotics

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ABSTRACT

Long development times and high costs prevent robots from being practical for use in many important field missions. Here a modular design approach is proposed to produce a rapidly deployable low cost field robotic system. An inventory of components such as actuated joints, links, power supplies, and software modules are assembled to produce a field robotic system for a specified task. The proposed design method uses a hierarchical selection process combined with a genetic algorithm to select a robot configuration and action plan for a given task. This method is applied to an inspection task required for the preservation of the USS Constitution, an historic naval ship.

1. Introduction

Mobile robots are needed to perform important tasks in field environments. Robots could remove humans from dangerous situations such as hazardous material clean-up, nuclear site inspection, bomb disposal, space exploration, and infrastructure inspection. Potentially, robots could prove economical for such applications as highway and bridge inspection and maintenance. Despite the anticipated advantages of robotic systems for field environments, they are not widely used. In large part, this is due to the long development times and high initial costs for systems that must generally be designed for a specific mission that may not be repeated. Such systems can require years to develop and cost hundreds of thousands of dollars. To be practical for many applications they should be ready in weeks or months and cost only tens of thousands of dollars. Clearly new design approaches are required.

In this paper a design approach based on modular components for field robots is proposed. It has the potential to allow field systems to be rapidly and cost effectively designed and fabricated. The approach is based on the use of an inventory of physical robotic modules such as actuated joints, links, and power units that are assembled in different configurations to perform different tasks. This approach also uses software action modules that are assembled to produce an execution plan for a given robot assembly and its task. Clearly, using pre-fabricated modules would greatly shorten development times. Also, substantial cost savings would be realized by using an inventory of reusable "standard" modules that could be used for a number of applications. In theory, even a relatively small set of modules can be assembled into a very large number of robot configurations. Some are feasible; some are not. The main question addressed in this paper is how to assemble the best system for a specified mission from a given inventory of modules in a reasonable amount of time. Throughout this paper the terms robot configuration, robot designs, and robot assemblies are used interchangeably to describe field robotic systems.

The task description, hardware inventory, and software inventory are used by a rapid design algorithm and rapid plan generator to create a system for the task. This paper will focus on the design aspect of the methodology. Section 3 explains the theory behind the rapid design algorithm. In section 4 an application of this method to an example task is explained. The results of the rapid planner are also shown in section 4. For a discussion of the planning method please refer to reference [1].

This design method uses a hierarchical evaluation and selection process combined with a genetic algorithm search to find the best design for a given task. This procedure is applied to the problem of designing a system to perform an inspection task on the USS Constitution, an historic ship of the United States Navy.

2. Background and literature

Substantial research on the design of mobile field robotic systems has focused on developing and studying different concepts for mobility such as walking, climbing, and crawling [2,3,4,5]. Some studies have attempted to develop design methods based on fundamental mechanics, such as developing design rules for motor selection to avoid actuator saturation and to minimize system power consumption [6, 7]. Research in the design of field robotic systems has largely focused on either the development of a specific technology or on a specific "one of a kind" system.

Recently, there has been important work in the design of industrial manipulators constructed of modular components. These studies have dealt with the mechanical design [8, 9], the kinematic modeling [10,11], the configuration selection based on computer aided design techniques [4], and design based on task requirements [12,13]. The industrial manipulators considered in these studies are quite different from field systems that must be capable of mobility as well as manipulation. The development of techniques to design field robotic systems using modular components has been virtually unexplored.

3. Modular design

The key to our approach in the use of modular components for field robotic systems is to apply fundamental engineering principles to reduce the size of the design space in a hierarchical series of structuring and tests. Then a genetic algorithm is applied to perform the final search in a very reduced design space. It should be noted that genetic algorithms can be naturally applied to this problem, as a design problem using finite numbers of modular components is completely consistent with the discrete nature of genetic algorithms.

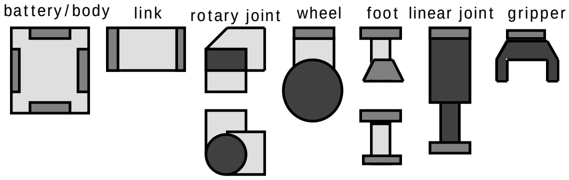


Figure 1. The Module Inventory

Figure 1 shows, schematically, a relatively small set of modular components. The actual inventory includes multiple modules of the same type. For instance, the inventory may contain three identical power supplies or five identical joint modules. Also, the inventory may contain modules of different sizes, such as large and small power supplies.

Combining this small set of modules in different ways permits many topologically diverse robots to be constructed. Three sample robot assemblies that can be produced from this inventory are shown in Figure 2.

These three robot assemblies are a small fraction of the possible assemblies the given inventory can produce. Even with high-speed computers, the combinatorial explosion of the number of possible robots precludes analysis of every possible assembly. For instance, using an inventory of 30 modules of 12 unique types yields 11 billion assemblies. If the evaluation of each assembly took only 1 millisecond, the computer would require 127 days to exhaustively search for the best assembly [14]. Clearly, evaluating the general performance of each design (say, via detailed computer simulations) would further increase this already excessive figure.

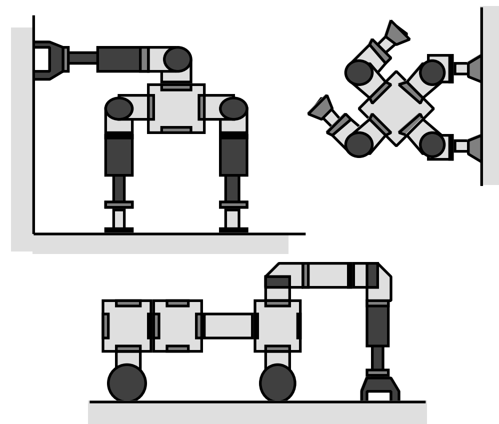
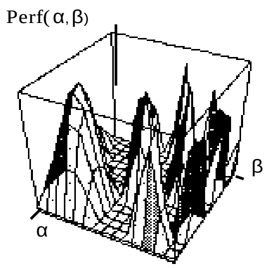


Figure 2. Sample Robot Assemblies

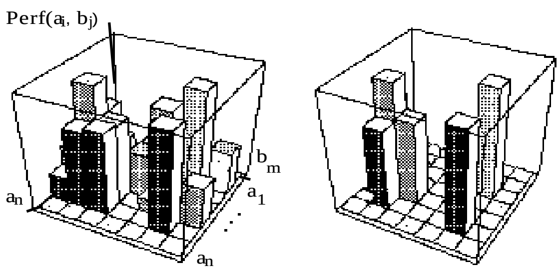
3.1 The modular design space

In some important ways, the design of a modular system can be simpler than the design of a conventional system. In modular design, the design space is composed of pre-existing components, therefore all characteristics of the components are known a priori. This is not true in a conventional design problem. Also, in a conventional design problem, the design variables are, in general, continuous, and the number of possible solutions is infinite. A conventional design space is shown schematically in Figure 3a. In this figure, the design's performance is plotted against two design variables. With modular design, the space is discrete. Solutions can only be composed of the discrete components within the inventory. While the number of possible solutions can be very large, it is finite. This space is represented in Figure 3b.

The number of possible solutions in this discrete space grows very rapidly with the number of available modules. For any real problem an exhaustive evaluation of these solutions is out of the question. The key to a practical search lies in reducing the design space to a computationally feasible size, as shown schematically in Figure 3c. This reduction is accomplished here with the use of a hierarchical selection process.



a) Conventional design



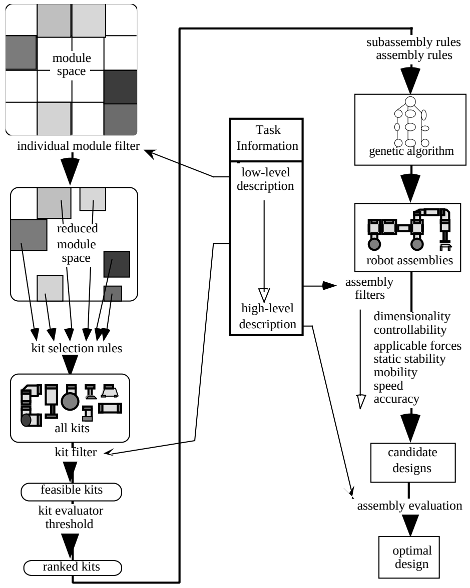


Figure 5. Modular Design Process

With the design space very substantially reduced, a genetic algorithm is used to search for the best designs. The genetic algorithm represents the robot assemblies formed from the kits with a tree structure or chromosome. This representation is shown in Figure 6.

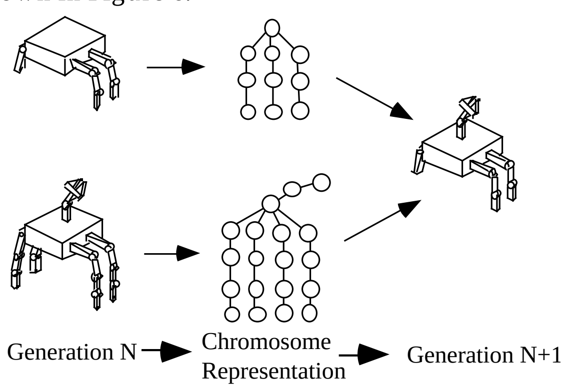


Figure 6. Genetic Algorithm Representation

The genetic algorithm takes a number of robot assemblies, called a generation, and combines some attributes from one assembly with those of another, thus creating a new generation of robots. In Figure 6, the limb from one robot is placed on a second robot to produce a third unique robot. This process is called crossover. The algorithm attempts to have new generations of robots that contain the best characteristics from previous generations. The algorithm may also add new characteristics that were not present in the previous generation; this process is called mutation.

The genetic algorithm uses assembly rules and filters to produce a fitness value for a given robot configuration. This fitness value is used to compare one assembly to another. An example assembly rule is that each robot limb must end with an end effector. A robot that did not meet this rule would have a very low fitness value. Assembly filters make estimates of system performance measures such as power consumption, applicable forces, static stability, and mobility.

Using the techniques of crossover and mutation a final robot configuration evolves after multiple generations. A full description of genetic algorithms can be found in [15].

4. Application of modular design to USS Constitution inspection task.

This research is being done within the context of the development of field robotic systems to assist in the conservation and preservation of artistic, historical architectural and archaeological treasures and monuments, with the *USS Constitution*, also know as *Old Ironsides* , serving as a demonstration project [16,17]. Old Ironsides is the oldest fully commissioned warship in the world, and a proud symbol of America's naval history. Her preservation is important.

The example problem discussed here concerns the mission of sub-ballast inspection. The area underneath the ballast in the hold of the ship is subject to damp, rot inducing conditions, as shown in Figure 8. It is impossible for workers to inspect this area except when the ship is in dry-dock and the ballast is removed. In order to facilitate more frequent inspection, the use of a small autonomous field robot to perform this inspection is being considered. It is proposed that a robot enter through the access port to inspect the area beneath the sub-ballast support. The robot would carry a video camera and sensors designed to detect and measure rot.

The first step in the modular approach to a mission such as this one is to define the task, environment, and to characterize the available module inventory. Table 1 shows the module inventory that is used in this example problem.

Knowledge of the task forms the basis for the process design rules and filters. Figure 7 shows schematically the inspection task and some of the requirements. This figure represents a section in the lower part of the ship that must be inspected for wood rot. The robot needs to be capable of climbing the 8.5" step into the inspection area and fit through the 5.5" narrowest path. The robot should weigh less than 20 lb. to allow easy deployment and should cost less than $1000. This cost assumes that a module inventory has already been designed.

Type	Mass (kg)	Dimension (cm)	Notes
electric power	.36	12x4x4	13.4 W-hr, 5 ports
electric power	.14	8x3x3	5 W-hr, 3 ports
pneumatic power	1.1	16x9x9	100 W-hr, 6 ports
link	.001	1x5.5x1.2	361 Nm support
electric joint	.7	3.5x15x6.5	1.02 W, 10 Nm support, 5 Nm apply, .91 rpm
electric joint	.08	1.5x6.4x6	.09 W, 1.2 Nm support, .3 Nm apply, .8 rpm
electric joint	.02	1x4.2x4	.05 Nm support, .1 Nm apply, .91 rpm
pneumatic joint	.9	5x20x7	5 W, 30 Nm support, 20 Nm apply, 1 rpm
pneumatic joint	.6	4x10x5	4 W, 20 Nm support, 10 Nm apply, 2 rpm
electric gripper	.03	1x5.5x5.5	.06 W, 6.45 Nm support, 3.0 N grip
pneumatic gripper	.5	3x10x10	5 W, 30 Nm support, 30 N grip force
foot	.005	1x2x1.5	126 Nm support

Table 1: A Module Inventory

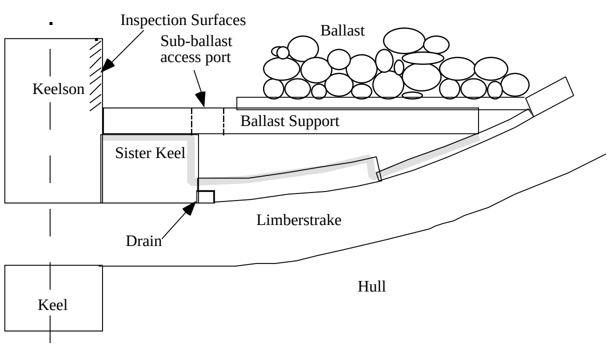


Figure 7. Sub-Ballast Inspection Task Definition

With the task and inventory defined, the hierarchical selection process uses several module filters in its first step. An example is that all modules must be small enough to fit through the small sub-ballast access port. One module that is eliminated by this module filter is the hydraulic power supply. This power supply module is too large to fit into the inspection area. With the elimination of the hydraulic power supply the filter that requires all actuators to have an appropriate power supply eliminates the two hydraulic joints and the hydraulic gripper.

Kit filters are than applied. An example kit filter used in the Constitution task is the maximum robot weight. All kits whose weight exceeded this maximum were eliminated. The genetic algorithm considers the surviving kits to evolve a final robot configuration. The genetic algorithm assigns a fitness to a configuration by making estimates of the robot's performance characteristics. An example of this is the robot's climbing ability. This is estimated based on the length of the robot's legs, for example a robot with 2" legs will not be capable of climbing the required 8.5" step. A result of this search is shown in Figure 8.

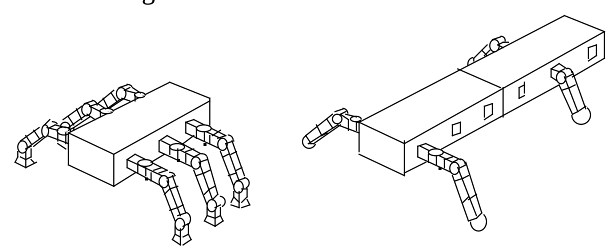
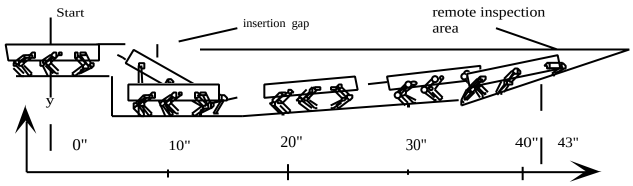


Figure 8. Robot Configurations for Inspection Task

The configuration on the left represents a robot that ranked high in the selection process. The robot on the right had a lower rank. The robot on the right weighs much more then the robot on the left. It has a longer operating time because it has two power modules and fewer joints. Also, the robot on the right costs less. However the robot on the left scores better in terms of climbing ability, ability to maneuver, dexterity, and walking ability while still meeting the cost and weight constraints. Higher ranking robots are finally evaluated using traditional design simulations.

Once the robot design process is complete and a robot configuration is determined, an action plan for the robot to complete the task is assembled from the software modules. An example software module is a function to command the robot to move its front right leg forward. Again a genetic algorithm and a simulation are used to evolve the required plan. Figure 9 shows a plan for one robot assembly applied to the inspection task. In this plan 33 action modules are assembled to produce a successful plan. For a more complete discussion of this planning work refer to reference [1].



The script for that trace:

1. body down	12. rotate CW	23. rotate CCW
2. rotate CCW	13. leg 6 forward	24. body forward
3. body down	14. leg 4 forward	25. leg 6 forward
4. bdoy forward	15. leg 3 forward	26. leg 5 forward
5. body down	16. body down	27. leg 3 forward
6. leg 5 forward	17. leg 1 forward	28. rotate CW
7. leg 6 forward	18. leg 3 forward	29. body down
8. body forward	19. body up	30. body down
9. leg 6 forward	20. leg 6 forward	31. leg 6 forward
10. leg 5 forward	21. rotate CCW	32. rotate CW
11. leg 6 forward	22. body down	33. leg 4 forward

Figure 9. Modular Robot Software Plan

5. Summary - conclusions.

In order to reduce the cost and development time of field robotic systems a modular design approach has been proposed. In this approach, an inventory of pre-existing hardware and software modules are assembled to quickly produce a system for a given task.

The modular design problem differs from conventional design in that the design space from which a solution can be produced is both finite and discrete. Although the space is finite, it is very large and increases rapidly as modules are added to the inventory. A hierarchical selection framework for searching this large space has been established. It prunes the design space to a manageable size. This reduced space is then searched for the higher ranking designs using a genetic algorithm. An action plan is also produced from software modules using a genetic algorithm.

This design methodology is applied to an inspection task for the USS Constitution. This design methodology may have important applications to the design of other types of systems.

6. Acknowledgments

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