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Design of a Reconfigurable Modular Manipulator System

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Abstract

Using manipulators with a fixed configuration for specific tasks is appropriate when the task requirements are known beforehand. However, in less predictable situations, such as an outdoor construction site or aboard a space station, a manipulator system requires a wide range of capabilities, probably beyond the limitations of a single, fixed-configuration manipulator. To fulfill this need, ~~we~~ Researchers have been working on a Reconfigurable Modular Manipulator System (RMMS).

Unlike conventional manipulators with fixed configurations, the RMMS will utilize a stock of interchangeable link and joint modules. Given requirements such as the workspace, dynamic accuracy, and the payload required to accomplish a task, the RMMS will design the most appropriate manipulator configuration, select suitable modules form the inventory, generate an assembly procedure, configure the controller, and finally apply the resultant manipulator to the task. In this way, the RMMS will fill a far wider requirement space than any single manipulator. It is also inherently easy to maintain and transport, since it can be readily assembled and disassembled.

Researchers ~~We~~ have designed and are constructing a prototype RMMS. The prototype currently consists of two joint modules and four link modules. The joints utilize a conventional harmonic drive and torque motor actuator, with a small servo amplifier included in the assembly. A brushless resolver is used to sense the joint position and velocity. For coupling the modules together, we use a standard electrical connector and V-band clamps for mechanical connection, although more sophisticated designs are under way for future versions. The joint design yields an output torque fo 50 ft-lbf at joint speeds up to 1 radian/second. The resolver and associated electronics have resolutions of 0.0001 radians, and absolute accuracies of ±0.001 radians. Manipulators configured from these prototype modules will have maximum reaches in the 0.5 to 2 meter range.

The real-time RMMS controller consists of a Motorola 68020 single-board computer which will perform real time servo control and path planning of the manipulator. This single board computer communicates via shared memory with a SUN3 workstation, which serves as a software development system and robot programming environment. ~~We~~ Researchers have designed a bus communication network to provide multiplexed communication between the joint modules and the computer controller. The bus supports identification of modules, sensing of joint states, and commands to the joint actuator. This network has sufficient bandwidth to allow servo sampling rates in excess of 500 Hz.

1. Introduction

Many applications of robotics in space will be different from the typical applications found in industry. Unlike conventional industrial manipulators which work in a precisely known and controlled environment, a space robot is envisioned as a backup astronaut, performing construction, maintenance, and experimentation. Such a robot must be capable of a wide range of tasks, from small scale, high precision operations such as replacing electronic components in faulty equipment, to immense scale, such as assembling room sized structures into a space station. Many of these tasks will be poorly defined or completely unexpected, particularly maintenance operations.

It is inconceivable to develop a single manipulator which meets even those requirements we can predict as necessary for a space manipulator. The level of dexterity and versatility provided by current manipulator technology is sufficient for only very constrained or well known operations. Nor is it practical, given the expense of transporting material to space, to maintain a large number of different manipulators at potential task sites. Our solution is the development of a manipulator system, which can be readily adapted to meet the individual constraints of each particular application as it occurs.

Designing a manipulator for a single, specific task is conceptually the same process as that employed now for conventional robot applications. However, at present the process of designing and manufacturing a robot system for a particular application is generally too long to be practical for the highly variable and urgent tasks that arise during space missions. To achieve the desired range of robot capabilities, streamlining and automation of the system configuration process are required.

In order to explore this approach, we are currently designing a Reconfigurable Modular Manipulator System, or RMMS. The RMMS is a collection of manipulator components or modules (links, joints, actuators, and end effectors), with a wide range of performance (length, strength, torque, speed, resolution, *etc*) utilizing common electrical and mechanical interfaces. This design allows a large number of different manipulators to be assembled, at the task site, from a small inventory of components. In parallel with the development of reconfigurable hardware, a similar software effort is underway to automate the generation of servo-controllor and path planning algorithms, provide a simple means of programming the manipulator task, and actually synthesize a workable manipulator configuration for a given task. Such a manipulator can thus be custom tailored to perform a specific task, and then broken down and re-used in a different configuration when a new task arises.

In a sense, the RMMS concept is an extension of conventional interchangeable manipulator end tools. To date, however, the major efforts in this area have been in the development modular hardware, so that a robot manufacturer can produce various manipulator configurations from standard sub-assemblies [1], or to allow remote maintenance of manipulators in hazardous (eg. radioactive) environments [2]. In contrast, the aim of our RMMS effort is to develop a manipulator system which is modular and reconfigurable by the user at the task site.

2. Design Philosophy and Implementation

An RMMS consists of the same major subsystems as those found in conventional manipulators:

- A physical structure made up of joints and links.
- Servo systems for each joint, consisting of actuators, transmissions, and sensors.
- A computer controller and programming environment.

The major difference between an RMMS and a conventional manipulator are the standardized component interfaces. This includes the mechanical mating of manipulator modules, the format of data communication, the communication protocols between hardware and software, and between various levels of software. Although adopting such standards impose inherent restrictions on the design of the actual components, this disadvantage is far offset by the interchangeability of manipulator components and the capability for rapid reconfiguration. In the following subsections, we discuss the conceptual design of each major component and interface in the RMMS we are developing, and the actual implementation in the prototype system.

2.1. Link and Joint Modules

The mechanical modules making up an RMMS are divided into two groups, joints and links. Links are simply structural elements, and joints are servo mechanisms, made up of sensors and actuators. When we represent the kinematics of a manipulator by a series of transformation matrices representing its links and joints, links have fixed transformation matrices, while joints have variable ones (a function of the joint variable). Electrical power is bussed and communication is multiplexed over a small number of conductors permanently installed in each module, allowing for simple assembly without custom cabling.

One implication of this modular joint design is that the *entire* joint actuator must be packaged *within* the joint module. Each joint module must include a motor (or some type of actuator), a transmission mechanism, a position sensor, and the necessary power electronics to control the motor. Although these design constraints limit the power which can be generated by the joint due to the limited size of the motor, transmission, and power amplifier, this is not viewed as a major short comming of the design, particularly for space applications. By properly selecting the transmission reduction ratio, high torques at low speeds can be obtained, which is appropriate for manipulating massive objects in near zero gravity (and also on earth) as long as speed of operation is not critical.

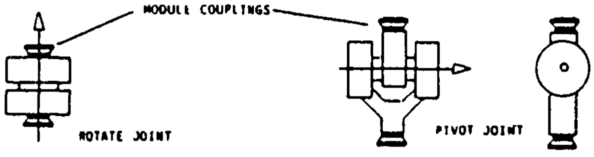

Figure 2-1: Modular Joint Assemblies

For simplicity and convenience, we are considering only the two common types of revolute joint in our RMMS. These two types are rotate, and pivot, and are distinguished by the orientation of the joints link axes with the joint axis. Both types of joint are shown schematically in Figure 2-1. A rotate type joint has link axes which are co-linear with each other and with the joint axis. A pivot has link axes which are both perpendicular to the joint axis.

Our current design for a pivot joint is shown in the photograph in Figure 2-2, and in the section drawing in Figure 2. The joint actuator is a conventional servo motor and linear amplifier driving a harmonic drive with 100:1 reduction ratio. This design yields a maximum output torque of 60 ft-lbf, and maximum axis speed of 1 radian/second. Also integral with the joint assembly is a brushless resolver mounted coaxially with the output shaft, providing position feedback with an accuracy of ±0.001 radian. If lower position resolution is acceptable, lower resolution (and less expensive) sensing electronics can be installed in the joint module. A wire windup allows the resolver (and output shaft) to turn up to 480° before damaging the resolver electrical connections. All of the actuator components are packaged in a sub-assembly of the joint module, allowing a number of different types of module to be based on common parts. The total weight of the joint is 25 lbs. A more compact and lighter version of this joint, as well as several kinematic variations on this basic design are currently under development.

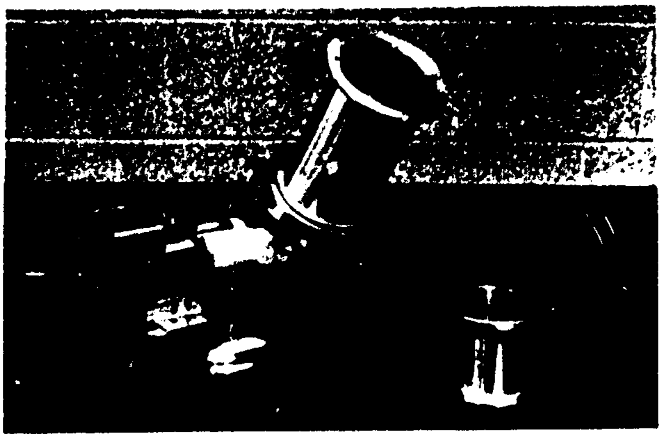

Figure 2-2: CMU RMMS Prototype Pivot Joint

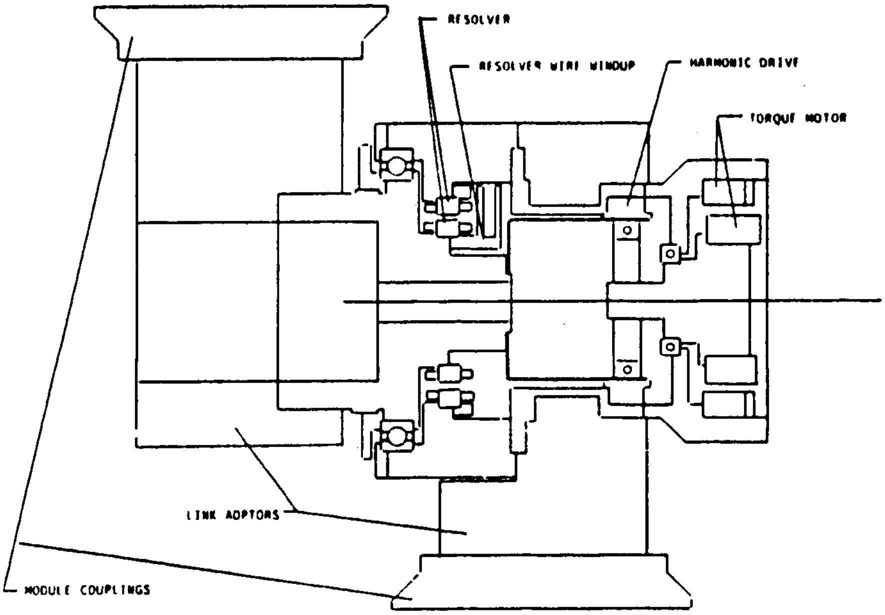

Figure 2-3: Section View of an RMMS Joint

2.2. Joint - Link Interface

In order to assemble the joint and link modules into a manipulator, a method of mechanically coupling the modules is required. This coupling must both align the modules, and lock them together with sufficient strength to transmit the internal forces generated by the movement of the manipulator. In addition to structurally coupling the modules together, this interface must also electrically couple the modules, and be able to sense the coupling orientation of successive modules.

The current interface design is shown in the photograph in Figure 2-4. An arrangement of pins and holes limit the coupling orientation to four, equally spaced positions. An LED in one flange and four phototransistors in the other allow the controller to sense which of the four possible orientations is in use. A commercial V-band clamp couples the two flanges together. As shown in the figure, the same coupling flange is an integral part of the link modules. Although rudimentary, this design provides the necessary functionality for the module interface. However it is not easily operated. Future versions will make use of either quick release V-band clamps, or a more sophisticated design with an automated locking mechanism to allow automatic "peg-in-hole" type coupling.

Figure 2-4: Prototype Module Interface

2.3. Communication Interface

As mentioned, each joint will contain the power and sensor electronics for the actuator. In order to control the joint actuators and obtain sensor feedback, a communication link between the joint modules and a computer controller is required. In order to allow standard connectoring between joint modules, this communication link must be implemented using a fixed number of conductors, yet be capable of supporting an arbitrary number of modules. This implies a multiplexed communication link, similar to a computer bus or LAN.

Due to the high overhead associated with existing LANs, our prototype utilizes a bus type implementation. The design is shown schematically in Figure 2-5. The bus design is based on a conventional 8 bit bi-directional data bus, an additional 5 control lines, and a rather unconventional 4 bit daisy chained address bus. The daisy chained address bus provides automatic node address configuration, that is, the first module in the manipulator is node address 1, the second module is node address 2, and so on. This is accomplished by including a "subtract one" circuit in each module which is in the path of the node address lines. Each joint can thus detect "address equals zero" as the node address. Due to the low data rate of the bus (current bus clock is 500 KHz), the propagation delay added by the subtract circuit is negligible.

2.4. Software Controller

In order to augment the capabilities of the RMMS hardware, a reconfigurable control and path planning algorithm are required. These algorithms would allow the control computer to automatically synthesize a control program for a given manipulator configuration and task requirement. This entails automatically deriving the manipulator forward and inverse kinematics, and inverse dynamics given the kinematic and dynamic parameters of the modules. This is one of the major research area of our RMMS project.

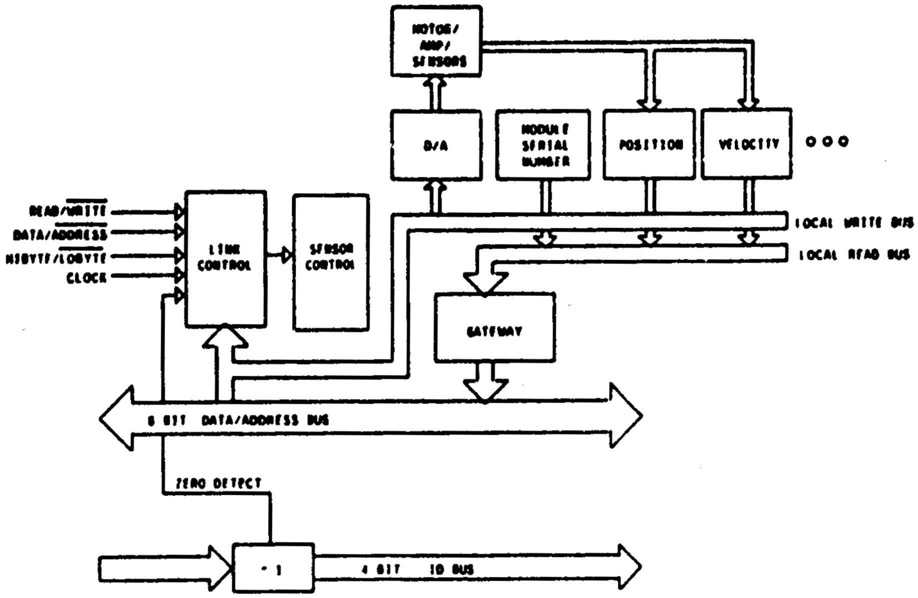

Figure 2-5: Manipulator Communication Bus Logic

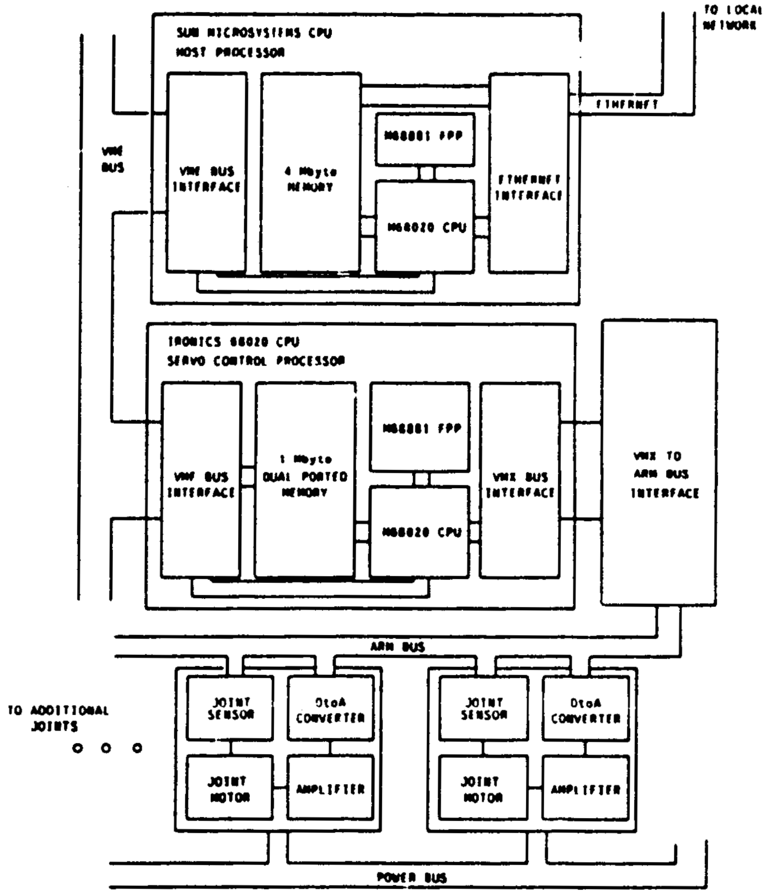

Figure 2-6: Schematic of RMMS Computing Architecture

2.5. RMMS Computing Architecture

The realtime control software in our RMMS runs on a dedicated *controller CPU*, with a hardware interface to the inter-module communication network. This controller CPU will perform the necessary realtime control of the manipulator, and receive commands from a second, *master CPU*. The intent of this architecture is to have the manipulator controller appear as a peripheral in a standard microprocessor system. Communication between the master and controller CPU will be via a number of memory mapped control and status registers maintained in shared memory on the controller CPU. This allows the controller CPU to be readily integrated into any master CPU system sharing the same system bus.

The present implementation of this architecture is shown in Figure 2-6. The controller CPU is an Ironics single-board computer, based on a Motorola 68020 processor and VME bus, with 1 MByte of dual ported RAM. The master CPU is a SUN3 workstation, also based on the Motorola 68020 and VME bus. The similarity between the two machines allows us to use the same editor and compiler for both processors, simplifying software development and inter-processor communication. The interface to the manipulator communication network is via the VMX bus interface included on the Ironics. The VMX bus is a recognized extension to the VME bus, intended as a local IO bus in multiprocessor systems such as this.

3. Span of Possible RMMS Configurations

In order to illustrate the range of capabilities of an RMMS, we have estimated several performance specifications for all of the manipulators possible given a reasonable size inventory of components. This set of specifications is used to classify the possible manipulators into groups with similar characteristics. By noting the number of different configurations within each class, we can gain an appreciation for the versatility provided by an RMMS.

3.1. Module Inventory

Based on our current design effort, let us consider an example RMMS with a module inventory consisting of:

- 25 joints, consisting of 5 sets with maximum joint torques of: 10 Nm, 30 Nm, 60 Nm, 120 Nm and 200 Nm. Each set consists of 3 pivot and 2 rotate joints.
- 12 joint position sensors, consisting of 3 each of the following resolutions. 10 bit, 12 bit, 14 bit and 16 bits.
- 20 links, consisting of 4 each of the following lengths: 0.1 m, 0.2 m, 0.5 m, 1.0 m and 2.0 m.

3.2. Obtainable Configurations and Range of Specifications

To limit the scope of this analysis, let us make the following assumptions:

- The manipulators will be 3 degree-of-freedom robots, made up of revolute joints, and will end in a conventional three axis (rotate-pivot-rotate) wrist. Thus the final joint of the three axis manipulator should not be a rotate joint, as this would be redundant.
- Two types of revolute joint assemblies will be considered: pivot and rotate, which are shown in Figure 2-1.
- Consecutive pivot joints must have either parallel or perpendicular axis orientations (in terms of the Denavit-Hartenburg convention $\alpha = 0^\circ$ or 90°).
- The orientation of the manipulator with respect to the world will be ignored.

Within these assumptions, there are seven basic meaningful manipulator configurations, which are shown in Figure 3-1. Within each of the seven configurations, numerous combinations are possible by using links of assorted lengths and assorted joint module designs, resulting in a wide range of manipulator performance.

The manipulator specifications we have considered in comparing the obtainable manipulator configurations are reach, tip force, and tip position accuracy. The specifications were defined as follows:

- Reach: length of the manipulator when extened. We use the sum of the link lengths as an estimate.
- Tip force: the minimum of the three joint torque capacities divided by each joints longest moment arm. Measured in Newtons.
- Accuracy: the root mean square value of the uncertainty in tip position due to the error in measuring the joint positions. Measured in meters.

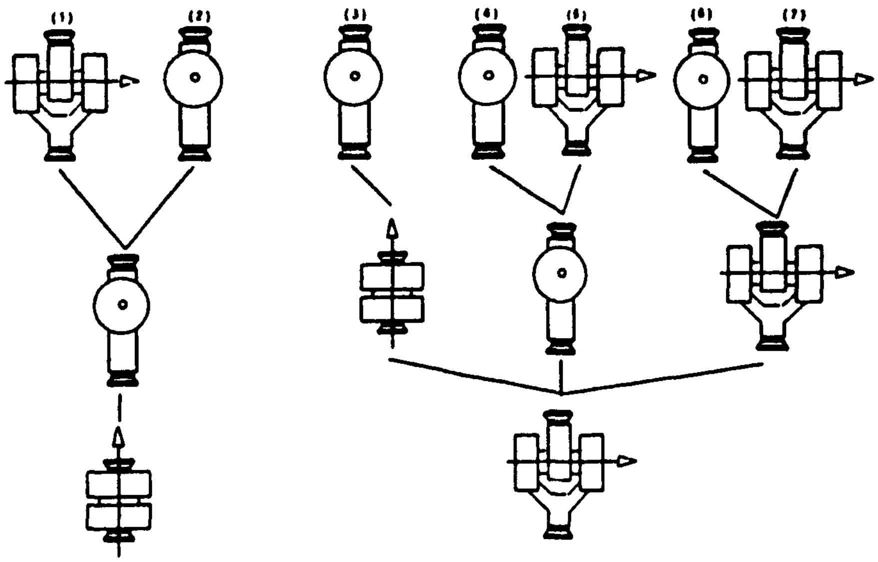

Figure 3-1: Meaningful Manipulator Configurations

We have calculated the number of obtainable arm configurations with various combinations of tip force, accuracy, and reach. The results are given as histograms in Table 3-1, which show how the obtainable configurations are distributed over the range of specifications.

We can interpret the histograms in Table 3-1 by considering the classification of typical robot tasks and performance requirements shown in Table 3-2. Ignoring speed requirements (which are generally imposed by economic thru-put constraints rather than the ability to perform a task) we can see that the obtainable range of manipulators spans each of the four major classes of task.

```
force

200 N      0   232   170    10    40     0     0     0     0     0
         104  1142   567   132    18     0     0     0     0     0
           0   132   125     6     6     6     0     0     0     0
           0   328   545    28    44     4     0     0     0     0
         212  1513  1772   706   220     0    26     0     0     0
           0  1497  1075   495   567    38     8     0     0     0
         170  2058  2555  2173  1306   188   202    14     4     0
         125  3136  4377  1350  3191   600   814   180    53     0
           0  4773  8994  7376 11028  1800  3589   913   207     0
 20 N      0     0  6595  5873 10643  2614  5861  1518   611     0   reach

        0.5 m                                                5.0 m
```

```
position error

0.05 m     0     0     0     0     0     0     0     0    16     0
           0     0     0     0     0     0     8    20    12     0
           0     0     0     0     0     0    72    60    44     0
           0     0     0     0    16    38   355   137    15     0
           0     0     0    16   303   114   723   120    97     0
           0     0     0   388  1751   521   360   217     1     0
           0     0   138  2115  2604   294   934    88    46     0
           0     4  2537   789   995   345   478   214    71     0
           0  2616  4617  2844  4715   832  1528   294    98     0
0.005 m  448  5892  6596  3256  3504   544   918   194    48     0   reach

        0.5 m                                                5.0 m
```

Table 3-1: Histogram of Obtainable Manipulator Configuration Distributions

4. Summary

An RMMS as described in this paper can provide a wide range of manipulator performance from a small amount of hardware. This is very important for performing tasks which are either poorly defined, often one time occurrences, or located in isolated environments. Examples of such tasks include nuclear plant maintenance and practically any type of manipulation required aboard a spacecraft. In addition to the increase in capability afforded by an RMMS, there are various side benefits to such a modular design which make it very attractive for commercial use, most notably the ease of maintaining, modifying, and updating such a system.

We are now building a small RMMS prototype. As of January 1987, two joint modules and four link modules have been machined, and are now being integrated with a computer control system. At the same time, theoretical work is under way to develop algorithms for generating manipulator kinematics, dynamics, and control. A major effort is being made to reduce the size and weight of the current joint design, which is a limiting factor in both manipulator speed and payload. First operation of the system is expected in the second quarter of 1987.

TASK SPECIFICATION	MANIPULATION PERFORMANCE REQUIREMENTS			
	REACH (meters)	PAYLOAD (Kg)	ACCURACY (mm)	SPEED (m/sec)
CLASS I	0.3 - 0.75	0.5 - 1.0	0.05 - 0.5	0.5 - 2.0
CLASS II	0.75 - 1.5	1.0 - 5.0	0.1 - 2.0	0.5 - 2.0
CLASS III	0.75 - 1.5	5.0 - 25.0	2.0 - 15.0	0.2 - 1.0
CLASS IV	1.5 - 3.0	1.0 - 5.0	2.0 - 15.0	0.5 - 2.0

Examples of typical class applications:

Class I -	precision assembly, printed circuit component insertion.
Class II -	small part handling, pick and place assembly, loading and unloading of machine tools
Class III -	large part handling, high contact force operations, surface grinding and deburring
Class IV -	seam tracking for welding or sealing, spray painting

Table 3-2: Manipulator Task Classification

Acknowledgments

The authors would particularly like to thank Mark DeLouis for his contributions to the RMMS design, and for machining and assembling the prototype RMMS hardware in time to appear in this presentation. We would also like to thank Regis Hoffman, Laura Kelmar, Pradeep Khosla, and Jim Moody for contributing their experience and ideas to the RMMS design, and a great deal of effort to its continual development and implementation.

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