

Chapter 1: Introduction

This dissertation will describe the mathematical modeling and development of an innovative, three degree-of-freedom robotic manipulator. The new device, which has been named the Carpal Wrist, has evolved from the initial stages of invention and concept development, through theoretical modeling, design, and prototype fabrication. The work presented in this dissertation is both unique and complete; unique in its creation of a kinematic model of a fundamentally non-traditional robotic wrist structure, and complete in that the model provides the information needed for design, development, and application in a wide variety of manipulator tasks at all levels of performance. Furthermore, while the kinematic and dynamic modeling presented in this document are specific to the new Wrist device, the modeling and analysis techniques have applications in other areas of parallel kinematics and robotics. In this respect, while the focus and intent of this report is to fully describe the theoretical modeling of a specific, parallel manipulator, it will also serve as a fundamental example of analytical treatment techniques for general parallel manipulators.

1.1 Background in Robotics

Flexible automation systems, or robotics, are becoming an increasingly important tool in this age of competitive, technology-driven production. Many industries are introducing robots into their operations to remain competitive and maintain flexibility over shorter product life cycles. Donald Vincent, executive vice president of the Robotics Industries Association pointed to the growth in demand of package handling among food and pharmaceutical manufacturers, saying, “the speed of robots are able to justify cost, ... The food processing industry is driven by speed, and robots have the speed to do product handling,” (<http://www.industr.net/discussions/robotics2.htm>). Increasingly, companies are choosing robots to work with or replace automation equipment for these high-speed tasks when they become more complex.

As demands on production, quality, and assembly in manufacturing settings and fully autonomous capabilities in remote settings are increased, manipulator technology must advance to meet these needs. Developments in the area of computer control and electrical sensory technology have been the most visible, allowing manipulators to become prominent in manufacturing settings and in replacing humans in service tasks. Meanwhile, R&D in the area of robot mechanics, particularly in developing new kinematic structures, has received much less attention. The vast majority of robotic architectures currently in use were developed in the 1970's. However, advances in robot mechanics with improved manipulator structures are critical to increasing the bounds on manipulator performance.

1.2 Robot Mechanics

Robot mechanics deals with the many aspects of kinematic and dynamic modeling, hardware design, actuation, and control. Manipulator kinematics is the study of the motion of the manipulator without reference to forces, i.e., the motion resulting from the kinematic constraints. Manipulator dynamics incorporates the kinematic model to relate robot motion to input forces. Other areas of robot mechanics include the following topics: mechanical design of the manipulator components, selecting suitable forms of actuation, meeting the available power supply, selecting joint and transmission elements, designing tool mounting capabilities, and providing protection from the operating environment.

1.2.1 Manipulator Kinematics and Dynamics

The fundamental task of a robot is to position and orient a tool in a specified manner. Position and orientation, taken together will be referred to as pose. The architecture of a robotic manipulator is selected and designed based on its ability to meet the tool-pose requirements. The most common manipulator architecture is a serial structure, a structure which consists of a series of actuated joints, (rotary and/or linear), forming one path between the tool and ground. To fully position and orient a rigid body in space, a six-degree-of-freedom (dof) task, requires a six-degree-of-freedom manipulator. Many tasks require less than six degrees of freedom, however. Therefore such tasks do not require a full six dof manipulator for operation. For example, tasks which employ an axis-symmetric tool do not require roll orientation. Some tasks require simple pointing orientation, a two-degree-of-freedom task, or spatial point positioning, a three-degree-of-freedom task. In some cases, a two or three dof manipulator will be used as modular sub-components in a larger manipulator system. For example, many six dof serial manipulators consist of two sub-structures; a three dof arm used to position the tool, and a three dof wrist used to orient the tool.

The mathematical model of each particular manipulator must be developed in order to provide the necessary control of the device. The mathematical model provides a mapping from the input space (also called joint space) to the output space (called tool space) of the manipulator. The input space consists of a set of coordinates that represent the controlled or actuated joints in the manipulator. The output space consists of a set of coordinates, typically a standardized coordinate set such as Cartesian coordinates and Euler angles, that describe the position and orientation (pose) of the tool. This mapping is referred to as kinematic position analysis. When the mapping proceeds from the input space to find the output space coordinates, it is termed forward kinematics. When the mapping proceeds from the output space to input space coordinates, it is termed inverse kinematics. For many serial manipulators this mapping is procedural, following the conventional Denavit-Hartenberg notation (1955) to describe the manipulator through a set of transform equations (Craig, 1989). Parallel manipulators result in highly non-linear kinematic position mappings. However, the mapping, once known, is performed as in all manipulators. The inverse kinematics or output to input space mapping is of most importance in manipulator control. Here, the output space is known from the desired

manipulator task and the inverse mapping generates the necessary input space parameters for control. To generally locate a rigid tool in space requires six independent parameters. Therefore, a fully general manipulator would be a six-degree-of-freedom (dof) device with six independently actuated joints. A manipulator with more than six degrees of freedom could accomplish the same task and would be termed redundant. A manipulator may also span only a part of the six degree of freedom space, for example, a three degree-of-freedom manipulator that provides orientation only, or conversely a three degree-of-freedom manipulator that provides position only.

Velocity analysis follows directly from position analysis. As in the position problem, the velocity or instantaneous kinematics takes the input velocity vector and maps it into the output velocity vector through a linear coefficient matrix, referred to as the Jacobian of the manipulator. This analysis is important in defining the size and quality of the available workspace of the manipulator. The available workspace is limited by singularities, and its quality is measured with a mathematical definition for dexterity. A manipulator exhibits a “singularity” when it loses one or more output degrees of freedom. Singularities become important when they exist within the kinematic workspace (the workspace defined by availability of kinematic position solutions), because they cause difficulties in kinematic control and limit range of applications. In addition to losing a degree of freedom, the dexterity of the manipulator, (a function of manipulator position and velocity direction) may show large variations throughout the workspace, demonstrating a poorly dexterous manipulator. Both the singularity and dexterity analyses are derived directly from the system Jacobian.

Finally, a dynamic analysis provides a third mapping between the input actuator torques and the resulting manipulator position, velocity, and acceleration parameters. In practice, a dynamic analysis relates the applied input forces to output inertial forces through the equations of motion. Equations of motion can be generated using various approaches. Newton’s Laws and Euler’s Rotational Equations, D’Alemberts Principle, and Hamilton’s Principle are common approaches for dynamic problems (Meirovitch, 1970, Kane, 1972). Further, the coordinate system used to describe the kinematics can be selected from either canonical forms, such as joint-space coordinates, or described using screw-system kinematics. Regardless of the dynamic approach or coordinate system used for analysis, the results lead to equations of motion which are unique to the physical device. Selection of approach and coordinates are important in deriving in equations that are tractable for manipulation, calculation, and that provide insight to the physical system.

Like the position mapping, the manipulator dynamics can be considered two directional: one a mapping which solves the forces required for manipulator motion, called the inverse dynamics problem, and one solving for manipulator motion given the input system forces, called the time response or forward dynamics problem. The inverse dynamics are necessary in control, when the manipulator trajectory is given and force requirements from the motors are needed. This problem is also useful in dynamic stress analysis. The time response or forward dynamics problem creates a simulation model of the device which can be used in advanced modeling, analysis, and in creating high-level controllers. In both analyses, the results of a dynamic

modeling become important when the manipulator is intended for high-speed operation or moving a massive payload, resulting in significant inertial loading.

1.3 Robot Architecture

The kinematic architecture of robotic manipulators can be classified as either serial or parallel (or a hybrid of the two). The serial architecture is predominantly used in application for a number of reasons. In many ways, it resembles the human arm and is therefore an intuitive concept. It has advantages such as a large workspace or range of motion. Most importantly, the serial architecture is relatively straightforward to model mathematically. For these reasons, the majority of research into the mechanics of robotics has been in serial devices. However, the serial architecture contains limitations that can only be partially improved through advanced actuation and controls technology. One limitation in particular is the single load-bearing path connecting the tool to ground.

An alternative, but much less common architecture for a robotic manipulator is the parallel structure. The key feature of this architecture is the multiple load-bearing paths that connect the tool to ground. Much like a truss is important in civil structures because of its high rigidity and high strength-to-weight ratio, parallel manipulators provide the same advantages in systems where accuracy and inertial forces are of primary importance. One common example of a parallel manipulator is the variable-geometry, octahedral truss, a special type of Stewart's platform, that is used frequently to provide base actuation in motion-capable flight simulators. Primary reasons for a lack of development of parallel-architecture manipulators are complications in modeling and analysis and the limited range of motion common to most parallel devices. Parallel architecture manipulators provide the possibility of improving manipulator structures if the necessary kinematics can be developed.

1.4 Robotic Wrists

Most manipulator systems can be considered as two distinct parts, an arm used to position and a wrist used to orient. There are many reasons for using this arm-wrist combination. First, this combination tends to decouple robot positioning and orienting functions. Second, this combination casts the robot into a form that is guaranteed to have a closed-form kinematic solution when the wrist motion is spherical (i.e., it provides orientation about a fixed point) (Craig, 1989). Not only does a closed-form position solution allow real-time control of the manipulator, it simplifies the kinematics which aids in motion control activities such as path planning and singularity avoidance. Third, this arrangement is conceptually intuitive and is readily adaptable to a great number of applications, since it approximates the human arm. Fourth, it helps reduce redundancy in the system and, therefore, helps eliminate singularities.

While the arm and the wrist are both necessary and both involve complex design issues, the wrist poses the greatest design complexity to engineers. The wrist must provide orientation about multiple axes, move about some center position, work in a relatively small envelope, and do this all while manipulating the entire system payload.

Robotic wrists are typically two or three degree-of-freedom (dof) devices, depending on their application requirements. General manipulators possess six dof, since complete pose control of a tool in space requires six parameters, three to provide position and three to provide orientation. In these cases, the wrist provides the three orientation components. Many practical robotic tasks require only five degrees of freedom at the output tool, for example when the tool is axisymmetric. The orientation provided in this case may be called pointing pose, since only two “pointing” orientational parameters are needed. This is common in tasks such as arc welding, spot welding, drilling, grinding, spray painting, and scanning operations.

1.5 Origins of the Carpal Wrist

The Carpal wrist concept evolved from work in the area of variable-geometry trusses, and other spatial parallel mechanisms. In particular, a spatial mechanism constant velocity coupling called the “Velocity-True” Coupling (VTC), (Canfield and Reinholtz, 1995, Canfield, Salerno and Reinholtz, 1994, 1995) provided a basis for the Carpal Wrist work. The characteristics of symmetry and simplicity in the all-revolute Velocity-True Coupling design were seen as positive components for industrial application. The mobility of the Velocity-True Coupling allowed orientation about a fixed center. The need for improved robotics in industry and the versatility of parallel mechanisms combined to give rise to the Carpal Wrist concept.

The Carpal Wrist has a spatial, parallel-architecture consisting of three symmetric 5-revolute chains connecting the ground (basal) to output (distal) plate (Fig. 1.1). This concept provides several inherent design advantages, including:

- A high strength-to-weight ratio, high rigidity, and improved dynamic characteristics
- Durability, stemming from its all-revolute design
- Symmetry of the structure provides advantages over many proposed spatial parallel devices;
 - It results in closed-form solutions to positional kinematics
 - It allows the wrist to behave in a spherical manner under proper kinematic control
- The possibility of either rotary actuation or linear actuation; rotary actuation providing high-speed response, linear actuation providing greater forces
- Direct actuation of base links allowing flexibility in locating actuators
- All actuated members are directly linked to ground, hence all input actuation is relative to ground
- A protected, enclosed central passageway
- A large, singularity free workspace

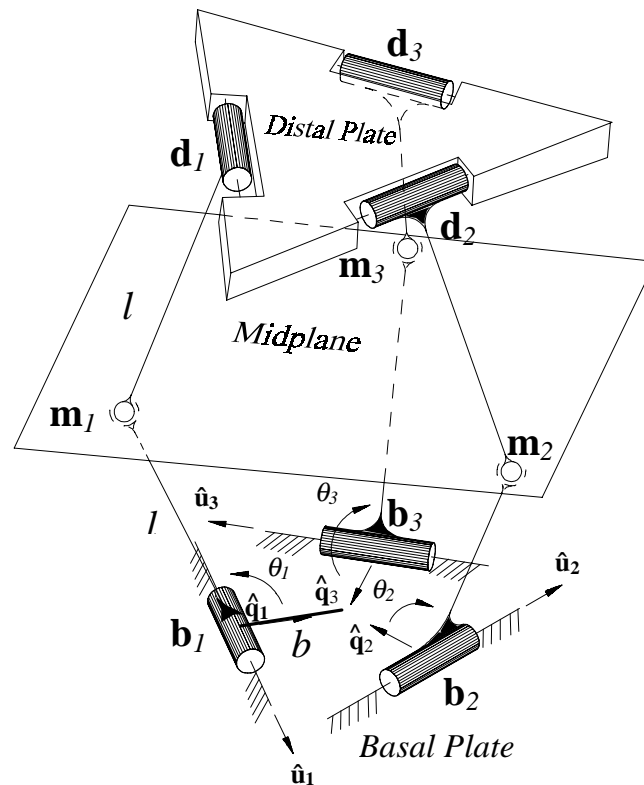


Figure 1.1: Kinematic Diagram of the Carpal Wrist

While these are general features of the proposed wrist concept, the relative advantages of the Carpal Wrist are best understood in context of existing wrist technology. A comparison of some key application requirements is made on a point-by-point basis in Table 1.1. Note that the Carpal Wrist has many of the advantages of general parallel-architecture wrists without sacrificing the kinematic simplicity and workspace size and dexterity of serial wrists. While the Wrist concept is not without disadvantages, it does have sufficient merit to warrant detailed kinematic investigation.

The Carpal Wrist has broad potential for commercial application. Forming this concept into a valid working model has involved a significant amount of research and development. The four areas of primary research are listed below:

- Positional Kinematic Analysis
- Instantaneous Kinematic Analysis and Control
- Dynamic Force Analysis
- Prototype Design, Implementation & Testing

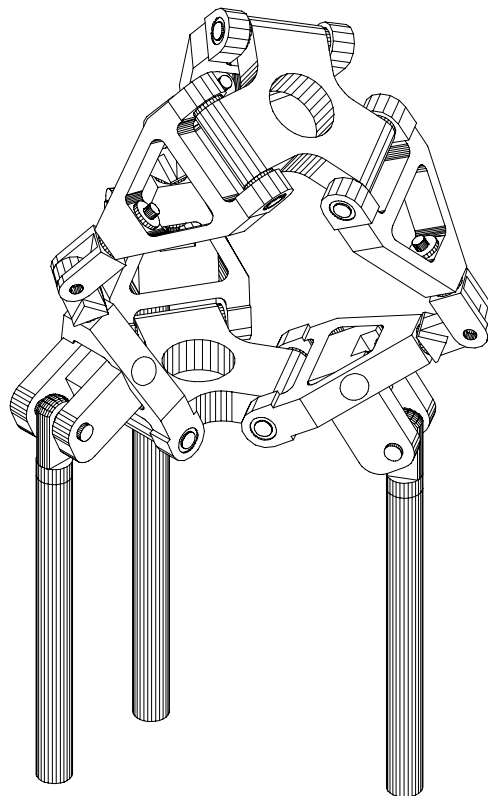
These issues have been addressed and validated, with the results summarized and presented in this dissertation.

TABLE 1.1: Features of Alternative Manipulator Structures

Attributes	Serial Wrists	Parallel Wrists	CARPAL Wrist
Positional Kinematics	Closed-form for many common arrangements	Implicit, usually requires numerical solution	Closed-form
Workspace / Dexterity	Roll-Pitch-Roll: Interior Singularities, large Workspace Roll-Pitch-Yaw: Boundary Singularities, Smaller Workspace Double Pointing Systems: Large Singularity-free Workspace	Typically limited	Large, singularity-free workspace, boundary singularities only
Strength-to-Weight ratio	Low	High	High
Actuation	Remotely located actuators Complex transmission required, Control axes relative to previous axis	Centrally located linear actuators	Remotely located actuators; Control all axes relative to ground
Routing Tooling Requirements	Generally external routing	Internal routing possible	Internal, protected-tunnel routing

1.6 Motivation for the New Wrist

Because of the importance of the wrist (orienting subsystem) to the entire manipulator system, improvement in robotic wrist design has been an area of great interest. From the review of previous research in robotic mechanics, there promises to be significant advantages in using parallel structures in manipulator design. The research performed in this dissertation, the development of the Carpal Wrist, has demonstrated a contribution to this technology by developing a robotic manipulator that can solve many of the problems associated with current and proposed wrists. A CAD drawing and a photograph of the Carpal wrist prototype are shown in Figs. 1.2 and 1.3. The remainder of this dissertation will describe the research that has created the modeling tools necessary to take the Wrist from concept to working application in industry.



**Figure 1.2: CAD Model of Carpal Wrist
Prototype**



Figure 1.3: Photograph of Carpal Wrist Prototype

1.7 Outline of Contents

This dissertation describes the theoretical development of the Carpal Wrist that has been performed to evolve the concept into a device ready for application in industry. An outline of this dissertation follows. Chapter 2 will provide historical perspective and background on the research and development of similar manipulator systems. The mathematical model of the Carpal Wrist will be developed and kinematic and dynamic analyses of this model will be performed in Chaps. 3 through 6. Chapter 3 will detail the position kinematics, Chap. 4 the instantaneous kinematics, and Chaps. 5 and 6 will develop the equations of motion based on the kinematic model. Chapter 7 will demonstrate application of the kinematic and dynamic model to implementation issues by investigating four areas of importance in implementation. Chapter 8 will conclude with a summary of the performed work and a projection on future work and application of the new robotic device. Finally, appendix A will describe the prototype that has been used to verify the theoretical models and has been presented to future industrial sponsors.