Chapter 2: Historical Review of Robotic Orienting Devices:

2.1 Serial Configurations

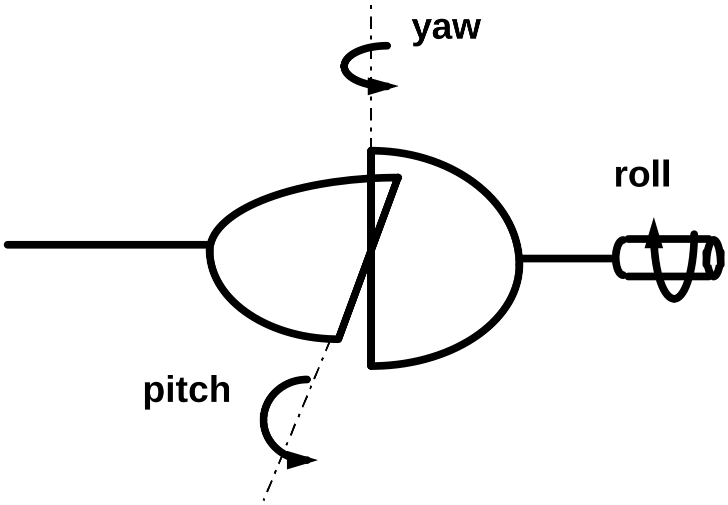

Figure 2.1: Gimbal Representing General Serial Wrists

The wrist plays a critical role in the performance of the overall manipulator system, Payload capacity, workspace, range of motion, and other performance parameters are often limited by the capabilities of the wrist. Therefore, robotic wrist design has been an area of prime interest among researchers and industry alike. Research in the mechanics of robotic wrists has focused on serial architecture manipulators. Because of the desired spherical nature of the wrist, the serial-type construction dictates that the revolute axes must intersect. Such wrists can be modeled as a gimbal, with the third axis attached (when needed) such that it intersects the first two. One example of the structure of such a wrist is shown in Fig. 2.1. The classical roll-pitch-yaw and roll-pitch roll wrists are directly derived from this model, based on the initial orientation of axes one and two, and the orientation of the third axis (Rosheim, 1989). From this basic model, many serial robotic wrists have been derived. Mark Rosheim has been at the forefront of robotic wrist research and has written a text cataloging the advances in serial robotic wrists (Rosheim, 1989). From this text, some of the more prominent serial wrists are mentioned. Several variations in the role-pitch-roll wrist have been proposed. The three-roll wrist, the wrist used on Cincinnati Milacron T3 robots was invented by Theodore Hahn Stackhouse in 1976 (Fig. 2.2) and has been a popular industrial application because of its range of motion. The three-axis wrist invented by Antonio J. Malarz and Gerald C.

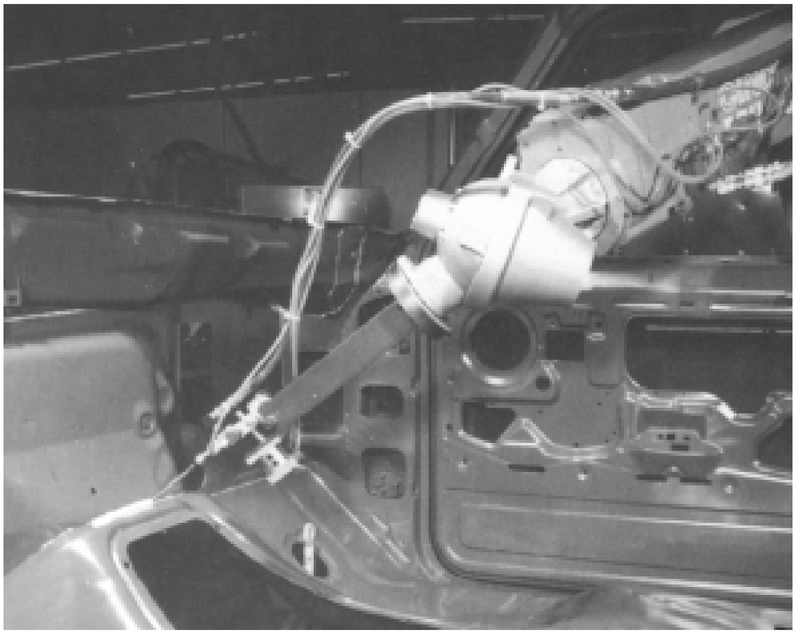

Figure 2.2: Cincinnati Milacron Three-Roll-Wrist (from Rosheim, 1989)

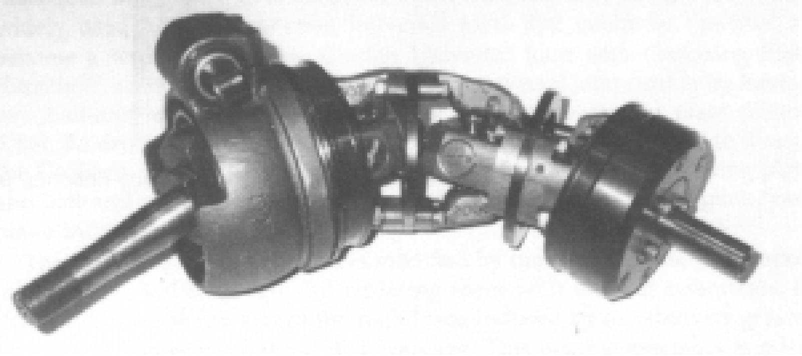

Figure 2.3: Slim Wrist by Graco Robotics Inc. Wrist (from Rosheim, 1989)

Rieck in 1983 is used on the General Motors Fanuc spray-painting robot and is unique because of its open inner cavity. The Prehensile wrist invented by Mark Rosheim in 1981 achieves very large pitch by providing pitch through two parallel axes.

Similarly, a large number of roll-pitch-yaw serial type wrists have been investigated. These include the Flexiarm, invented by Ole Moulag in 1977, which is used on the DeVilbiss robot and consists of three redundant Cardan joints. Moulag also developed the Slim Wrist (Fig. 2.3) produced by Graco Robotics Inc., which contains four redundant Cardan joints. Susnjara and Fleck (1982) invented a wrist consisting of a double universal joint connected by miter gears. Trevelayn worked on the ORACLE ET wrist, a double-universal design for shearing sheep in 1986. Stanisic and his colleagues have worked extensively on the SADPS, Symmetrically Actuated Directional Pointing System (1990). This wrist provides a very large singularity free workspace. Rosheim also invented the Robot Wrist Actuator in 1984, and the Omni wrist (Fig. 2.4) or Compact Robot Wrist in 1986 which consists of a pair of geared universal joints and a unique means of actuation. Veljko Milenkovic (1987) invented a double universal, linkage connected, nonsingular robot wrist in 1985 for Ford Motor Company to be used in spray painting. The Ex-Cell-O wrist, developed by Byrd Johnson Company in 1980 consists of hydraulic vane actuators located on the three intersecting axes. The Pitch-Yaw hydraulic wrist invented by Rosheim in 1980 has two semicircular, double-acting hydraulic actuators that share a common center.

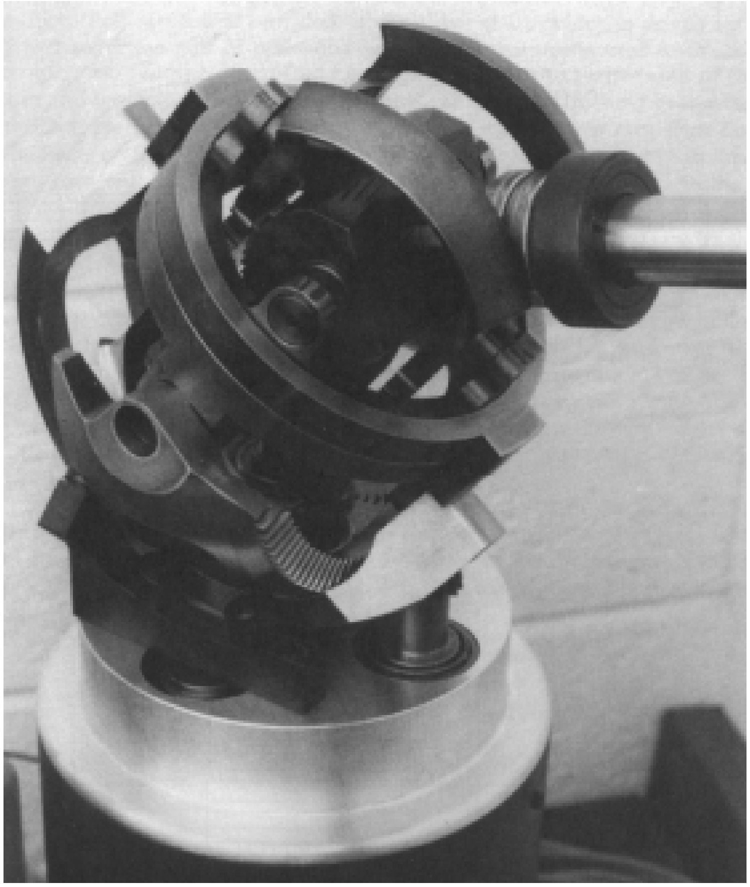

Figure 2.4: Omni Wrist Wrist (from Rosheim, 1989)

The work carried out on serial wrist are variations of the common intersecting revolute structure, shown in Fig. 2.1. The differences between these designs are primarily in the details such as actuation, maximizing range of motion, and the like. Several disadvantages exist in these wrists. In roll-pitch-roll wrist, the most severe limitation is the centrally located singularity zone. A singularity is a position or set positions where the manipulator loses one or more degrees of freedom. When these singularities exist, extreme care must be taken to avoid moving the robot near positions of singularity in operation, since a move into a singularity zone generally results in manipulator "lock-up". In addition to problems with singularities, actuation can pose design problems; actuation of serial wrists generally requires multiple concentric drive shafts or similarly complicated control method. In roll-pitch-yaw wrists, limitations can include a restricted workspace, existence of singularities, and difficulty in providing actuation.

2.2 Parallel Configurations

To a much smaller extent, parallel robot wrists have been proposed and investigated. A parallel structure has several load-carrying branches that connect the input and output members. These parallel wrist devices can be broken into two general configurations, parallel spherical wrists, and parallel spatial wrists.

2.2.1 Parallel, Spherical Wrists

Several researchers have proposed and investigated spherical three dof parallel manipulator devices (Fig. 2.5). These include Cox and Tesar (1989), Craver (1989), Asada and Cro Granito (1985), Gosselin and Angeles (1989, 1994) and Hunt (1983). Prototypes of these spherical manipulators have been developed by Craver (1989) and Asada and Cro Granito (1985). These spherical three dof parallel manipulators have three branches attaching the output member to ground, (making them parallel); these branches are triple-revolute joint chains, and have all revolute axes intersecting at a common point, called the wrist center. Gosselin and Angeles (1989) proposed a design where all the actuator axes (axes of the grounded link) are coplanar, symmetrically located at 120 degree intervals. The intersection of these actuator axes defines the wrist center. Gosselin, Sefrioui, and Richard (1994) looked at a similar structure, but with the output or gripper plane axes coplanar and symmetric. In the special case where both input and output revolute axes are coplanar, the three dof wrist must assume a planar configuration at a neutral or undeflected position; all revolute axes in the system lie in a plane at this neutral position. The purpose of this model was

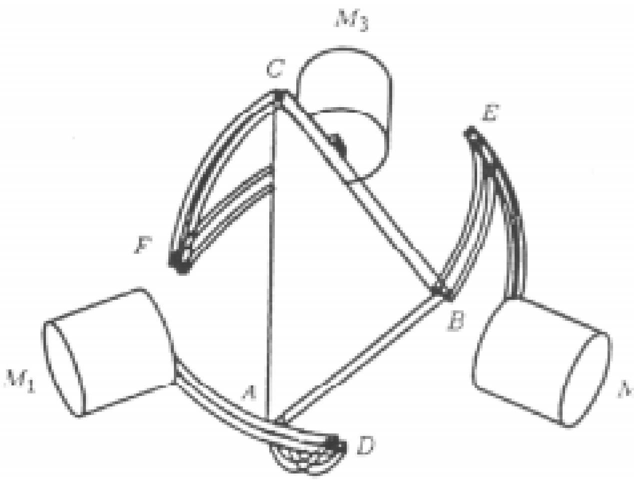

Figure 2.5: Parallel Spherical Manipulator

to allow a closed-form inverse and forward kinematic solution to be found.

Hunt (1983) demonstrated that inverse kinematics of parallel manipulators may be much easier to solve than the forward kinematics. As proof of this, Gosselin and Sefrioui (1991) show that a simple, planar, three dof parallel manipulator does not have a closed-form forward kinematic solution. Therefore, the advantage in looking at spherical parallel devices that contain symmetry, and/or coplanar axes is that they may contain closed-form positional kinematic solutions. Cox and Tesar (1989) and Craver (1989) discuss the characteristics of a three dof spherical parallel module with all joint axes intersecting at one point, the module center. They propose the use of this device as a shoulder module in a hybrid robot manipulator. Gosselin, Sefrioui, and Richard (1994) develop the direct kinematics of a general, three dof spherical parallel manipulator. While they call these general, these authors rely on symmetry to develop closed-form direct kinematic solutions.

These devices, while containing the strength and rigidity advantages of parallel mechanisms, also contain limitations that may be preventing their widespread use. Most significantly, they are limited in workspace, particularly in rotation about the pointing direction (roll). In addition, design and manufacture of these devices with multiple intersecting axes will be difficult.

2.2.2 Parallel, Spatial Wrists

A third general class of kinematic devices that have potential for use as robotic wrists are parallel, spatial manipulators. The best known parallel spatial manipulator is the Stewart's platform. The Stewart platform, shown in Fig. 2.6, consists of an input plate or base, and an output plate or platform. Connecting these are six, axially actuated links, providing six controlled degrees-of-freedom between the base and platform. This manipulator was first developed by Stewart (1965) for use as an aircraft simulator. Hunt discussed the use of Stewart's platform as a more general manipulator (1978, 1983), Fichter and McDowell investigated kinematic issues for its use as a manipulator (1980), and Fichter also investigated the kinematics (1984) and practical considerations (1986) for implementation of the Stewart's platform as a manipulator. Smith and Nguyen (1991) developed a parallel wrist based on the Stewart's platform. This wrist has many of the advantages of parallel construction but is limited in workspace size and possibly dexterity. Hudgens and Tesar (1988) introduced a parallel six-legged platform micromanipulator system located next to the end effector to compensate for robot positioning errors. In this micromanipulator, a parallel architecture was chosen to improve its rigidity, load capacity, and compactness. Others have investigated novel design modifications of these fully parallel actuated manipulators. Gosselin (1991) and Cleary and Arai (1991) have further refined these devices using linear actuation. Pierrot, Dauchez, and Fournier (1991a, 1991b) have worked on a six dof parallel device using rotary actuation as opposed to the linear actuation used in the standard Stewart platform models. Their design contains six Spatial, triple-Revolute (SRRR) chains. They call this manipulator the HEXA and claim it is ideally suited to perform high-speed six dof insertion tasks.

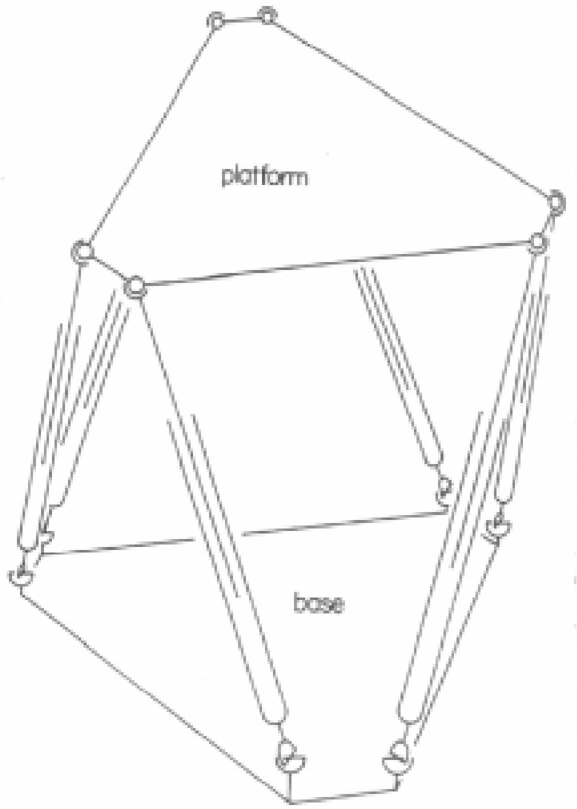

Figure 2.6: Parallel, Spatial Manipulator

Spatial mechanisms having other than six degrees-of-freedom have also been investigated. Clavel (1994) patented the DELTA manipulator, a high-speed three dof wrist, which was the basis for the HEXA manipulator, and contains three symmetric parallelogram-revolute-revolute chains. Salerno (1993) proposed and investigated the use of a three dof spatial unit as an orienting cell to create a modular, long-reach, truss-type manipulator. The modules in this long-reach manipulator are designed as truss elements, all members are loaded in pure tension or compression, and are called Variable Geometry Trusses (VGT's). Wang and Gosselin (1996) investigated the kinematics of a spatial four dof parallel manipulator. Two variations of this spatial manipulator were investigated, one with linear and one with rotary actuation. These manipulators were made of four Revolute-Revolute-Prismatic-Spheric (RRPS) and triple-Revolute-Spheric (RRRS) chains for the linear and rotary actuation respectively. Also, both had a five Revolute-Revolute-Spheric(RRS) chain to constrain the output motion to four dof. Lande and Dacid (1980) developed a two dof spatial parallel wrist that contains two, four-Revolute (RRRR) linear actuated chains, and a third four-Revolute (RRRR) fixed-length chain to constrain the output motion to two dof (Rosheim, 1989). The Cranfield Institute of Technology further refined this basic design and developed their own version of this wrist (Rosheim, 1989). Collins and Long (1994) investigated a six degree of freedom in-parallel telerobotic hand controller. This work demonstrates the flexibility in designing spatial parallel manipulators to meet the variable-freedom systems required.

While several spatial parallel devices have been proposed and researched, the research has not addressed some of their disadvantages that may be preventing these from becoming widely accepted in industrial robotic application. It is generally agreed that these parallel architectures are inherently strong and rigid relative to their weight. However, they have at least three significant limitations that include: 1) These manipulators often have a very limited workspace. This is in part due to the requirements for linear actuation, which limits range. 2) These manipulators often lack closed-form kinematic solutions. 3) Actuation of these manipulators may be slow, often due to the use of linear actuators.

2.3 Analytical Methods

Literature on analytical kinematic and dynamic methods are numerous, well accepted, and available in many engineering texts (for example, Craig (1989), Kane (1972), Mabie and Reinholtz (1987), and Meirovitch (1970)). Applications of various analytical approaches on mechanisms and robotics are also numerous in literature. To provide immediacy of important literature in this dissertation, reference to specific and applicable work will be presented at the introduction of each analysis.