A Class of "Parallel-Serial" Manipulators and Their Application to Material Handling Automation

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Introduction

The manipulating robots recently performing the material handling in the semiconductor industry can be classified into three major categories: robots with up to 4 Degrees Of Freedom (DOF), working in cylindrical coordinates; universal articulated arms with 6 or more DOF; and hybrid parallel-series manipulators with 6 or more DOF combining together the motion characteristics of the cylindrical robots and of a special kind of closed-loop mechanisms, available in the industry since the early 1980s. Regardless of the differences in the mechanical properties and motion characteristics of the robots from the different categories, the requirement imposed to them by the manipulating tasks they perform are always the same: *fast and reliable material handling; long reach for small footprint; compact size and light weight; motion efficiency and ability to comply with the mechanical constraints imposed by the equipment; high ratio of the payload and the weight of the robot; cost-effectiveness, etc.*. For more than a decade the cylindrical TRZ robots have been favorably used in a variety of processing machines, until the in-line equipment placement was imposed and identified as a standard by I300I. Being especially designed to work with radially arranged modules the TRZ robots became deficient to serve in-line arranged equipment because of lack of degrees of freedom. Another challenges to these robots lately inspired by the chipmakers are associated with the increased wafer sizes and the weight of the special end-effectors guaranteeing non-contact (based on Bernuli's principle), or edge-gripping support of the wafers. Due to the combined weight of the substrate and the end-effector, the manipulating arms deflect, which makes the constrained manipulating task difficult or impossible to achieve. To meet the requirements imposed by the non-radially placed equipment and to address the arm deflection issues, another kind of manipulating robots has been introduced in 1997 and referred to as "Global Positioning Robots (GPR)" by their ability to arbitrarily (globally) placed a rigid-body within the working envelope. The mechanical properties of these robots allow for effective and reliable high-weight material transfer between arbitrarily (in-line or radial) arranged equipment even if there are limited uncertainties in the placement of the source cassettes (FOUPs) or the process modules. This article aims at outlining the basic mechanical properties and functional characteristics of the GPR and to identify typical fields of their application.

Manipulating tasks and requirements imposes to the material handling devices

To comply with the physical limitations imposed by the semiconductor equipment, the substrate handling systems have to provide a constrained straight-line motion of the center of the wafer coincident with the longitudinal axis of the equipment. Ideally, the straight-line segment lies in a horizontal plane, but in reality the linear motion may require a synchronized vertical move to account for equipment placement inaccuracies or deflections of the robotic-arm. "Constrained motion" doesn't mean that the manipulated object comes in contact, continuous or intermittent, with the equipment. It rather reflects the fact that the path of the center of the wafer is constrained to stay within a close vicinity of the center-line of the equipment, which is usually less than 0.5 mm along the path, and less than 0.05 mm at the terminal point. That's why this motion is also referred to as "fine" motion. In addition to the constrained straight-line motion, there is another motion, referred to as "gross" motion. It is intended to transport wafers between different approach positions, which are the positions just in front of the equipment and is restricted only by the walls of the mini-environments. Because there is relatively high tolerance between the minimum-swinging envelope of the robot and the wall-constraints (as compared to the straight-line motion), this motion requires less accuracy. For the sake of increasing the performance of the robotic handling systems, the gross motion has to be very fast, and limited only by the requirement to securely hold the wafer on the end-effector. Blending (combining together) the constrained straight-line motion and the less accurate but fast gross motion is one of the challenges in the design and control of high-performance robots.

Mechanical properties and functional characteristics of the parallel manipulators

From structural perspective, the GPR comprises a closed-loop 3 DOF-mechanism that performs vertical, roll, and pitch motions, and an open-loop mechanism with three or more DOF that provides planar motion of the manipulated object. The closed-loop mechanism belongs to the class of the so-called "Parallel Manipulators". The first parallel manipulators have been introduced by analogy to the "Steward Platform" [1] in early 1970s. The interest towards parallel manipulators increased rapidly after the 1980s and recently there has been a well established theory of the parallel manipulators supported by a number of industrial applications [4]- [10]. Analogies (duality) between the mechanical properties of parallel and serial manipulators have been also established [10] to allow for direct implementation of the design and control methods already developed for the well-known serial manipulators to the respective parallel equivalents. From structural perspective, the parallel manipulators comprise a base and a platform connected to each other by means of single degrees of freedom actuating modules (members) arranged in parallel. The position and the orientation of the platform are controlled through the length of the parallel members. The advantages of the parallel manipulators over the serial manipulators are their higher accuracy, increased stiffness, better modular design, and simpler inverse kinematics. In the serial manipulators, the positional accuracy of the terminal link is a superposition of the accuracies of the consecutively arranged joints and links. The links and the joints that are closer to the base have greater contribution to the cumulative accuracy of the platform. In the parallel manipulators the distribution of the inaccuracies is quite different - the inaccuracies associated with the parallel members and the connecting passive kinematic joints do not superpose and all the members have the same contribution to the accuracy of the platform. The parallel architecture of the links guarantees even distribution of the external forces applied to the platform between the parallel members. In addition, the last are connected to the platform through higher order passive kinematic joints, which makes the parallel members be a subject of a partial, less than six dimensional loading. In some particular cases of spherical passive kinematic joints, the parallel members are subject to one-dimensional loading (extension/compression) only. This guarantees high stiffness of the parallel structure even if the connecting members are made with very small cross-section. The parallel manipulators can withstand significant external forces and are capable of supporting additional manipulating structures attached to the platform. Another advantage of the parallel manipulators is their simple inverse kinematics, which is a prerequisite for effective and accurate control. Because the connecting members are typically single DOF mechanisms, the inverse kinematics of the great majority of parallel manipulators is straightforward and singularity free. This provides for simple transformations of the motion from the tool space to the motor space and helps at the development of computationally effective continuous path control algorithms. The limited working area of the parallel manipulators is considered a drawback and that's why the parallel manipulators have been identified as an ideal choice for small and precise fine motions.

Figure 1: A "Parallel-Serial" GPR

Parallel-Serial Manipulators and the GPR Concept

In 1997, to combine the wide motion range and the dexterity of the serial manipulators with the preciseness of the parallel manipulator in small motion range, Genmark Automation, Inc. introduced a hybrid "Parallel-Serial" manipulator called the "Global Positioning Robot", or "GPR" (Figure 1). The GPR series meets the requirements for precise and fast wafer handling in the face of environmental uncertainties and arm deflections. In many substrate-handling applications, the robot is required to vertically move the wafer or to tilt it during the fine motion. This requirement becomes even stronger if there is an uncertainty in the equipment placement or if the robot-arm deflects due to the weight of the manipulated object. In order to precisely match the orientation of the equipment, the robot must be able to change the orientation of the end-effector by rotating around the axes of the coordinate frame firmly affixed to it. Orientation changes in the range of ±1.5 degrees account for the majority of the equipment placement deviations and deflection ranges. After the deflection is compensated, the plane of the wafer becomes angularly shifted with respect to the plane of the arm-motion. The amount of the shift is proportional to the amount of the deflection compensated. To guarantee that the orientation of the substrate matches the orientation of the equipment, and that the substrate stays in one and the same plane while being retracted from the process chamber, the end-effector should be able to rotate around the axes of the firmly attached to it coordinate frame. Typical examples of such rotations are the "roll", "pitch" and "yaw" motions. The first two motions are performed by the parallel mechanism of the GPR, whereas the "yaw" motion is provided by the open TRY kinematic chain attached to the top of the parallel mechanism. In particular, the open-loop mechanism attached to the platform may comprise an extended (up to 360 degrees) "roll" motion for substrate flipping and accurate positioning (Figure 2).

Figure 2: A 7 DOF GPR with servo controlled "roll" motion

The structural dexterity of the GPR makes it possible to fully automate their "teaching" through interactive control schemes and information from appropriate sensor arrays. The enhanced stiffness and accuracy of the parallel manipulators makes it possible to design long reach manipulating systems with dual-end effectors (Figure 3) or with dual-arm (Figure 4) intended for fast wafer swap, considered to be one of the most important factors for increasing the performance of the wafer processing machines. The prerequisite for a fast wafer swap is the availability of a second independently driven arm ready to place an unprocessed wafer into the process chamber as soon as the first arm takes the processed wafer from the chamber. The dual-arm concept considerably shortens the wafer exchange time and eliminates the extra movements from the process chambers to the source cassettes as with the single arm concept. A new design of a dual-arm robot from the GPR series, with less moving masses and better dynamic performance, was introduced in 1999 as an alternative to the dual-arm robots on a track - Figure 4. The new robot named the "GPR-Swap Master" inherits the stability of the GPR and the dexterity of the anthropomorphic robots. The robot combines the functionality of a three-link serial arm, which performs fast linear motion, with the motion of two lightweight arms for fast wafer swapping at the process chambers, source cassettes / FOUPs, prealigners, etc. The decoupled mechanics of the robot contribute to its modular design, simplified control, teaching, and programming. An exemplary motion of the GPR-SM between two in-line stations is shown in Figure 5.

Figure 3: An extended reach, dual end-effector GPR

Another typical application of the GPR is performing the material handling in vacuum environment. The substrates are held to the end-effector by gravity, edge-gripping, or non-contact means, which typically makes the end-effectors heavy and difficult to be carried by

Figure 4: An extended reach, dual-arm GPR for fast wafer swap.

conventional (TRZ) manipulating arms. The hybrid mechanical structure and inherent stiffness of the GPR makes them an excellent solution to the material transfer automation in the vacuum cluster tools. A high-payload (more than 5 kg.) vacuum robot with extended reach and vertical stroke is shown in Figure 6.

Figure 5. GPR-SM in motion

Conclusion

The advances in the mechanics and control of manipulating systems during the last decade identified the closed-loop mechanisms as an alternative or an effective addition to the widely used in the wafer handling open-loop mechanisms. The hybrid (parallel-serial) manipulators, represented by the GPR, have proven their ability to optimally combine the advantageous mechanical properties of the parallel and serial manipulators thus becoming one of the most effective means for performing the material handling in the semiconductor automation.

Figure 6: A high-payload GPR robot for vacuum applications

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