High-Performance Wafer Handling Systems for Semiconductor Automation

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Introduction

Nowadays, the overall productivity of the semiconductor FABs is becoming more and more dependent on the performance of the robotic systems, responsible for material handling within the front-end and back-end mini-environments. Regardless of how long particular processes take, the time for exchanging an already processed wafer, with an unprocessed one, is always becoming a bottleneck in the urge to increase the performance of the processing machines. To comply with the increased performance demands, while maintaining high accuracy and reliability requirements, the wafer handling robots have to be driven faster within the mechanical constraints imposed by the processing machines, as the cost and the size of the manipulated object significantly increases. The directions in which the manufacturers of wafer handling equipment concentrate their efforts are the design of mechanical systems with improved manipulating capabilities, direct-drive actuation, implementation of advanced control schemes, and last but not least - optimal application of the wafer handling equipment through careful analysis of the manipulating task via elaborate case studies, mathematical modeling, simulation and on-site experiments.
This article aims at addressing some of the approaches to increasing the performance capabilities of the robotic wafer handling system from both, a mechanical and a control point of view.

Description of the manipulating task

The common characteristic of the manipulating task performed by the robotic handling systems (RHS) is that they have to provide a constrained straight-line motion of the center of the wafer. This straight-line segment is coincident with the center (longitudinal) axis of the equipment (an open cassette, FOUP, a process chamber, etc.). 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. Characterizing the straight-line motion as "constrained" 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 very often referred to as "fine" motion. Depending on how the straight-line segment is situated with respect to the center of the robot, there are different approaches to performing the manipulating task, and different mechanical structures of the RHS, respectively.

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 RHS, 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 issues in the design and control of high-performance RHS. In many cases, effective blending of the "fine" and the "gross" motions contributes more to the decrease of the wafer exchange (swapping) time than to the increase of the velocity and acceleration of the separate motions.

Scenarios of Equipment Arrangement and Robot-Arm Architectures

The first and the most frequently used yet scenario of equipment arrangement in the semiconductor automation is the radial scenario. Within it, all the equipment modules are arranged so that their longitudinal axes go through one and the same point, coinciding with the center of rotation of the wafer-handling robot. The last works in a cylindrical coordinate frame and the only straight-line motions it can perform are the radial ones. It could be said that the radial scenario was chosen to mostly comply with the limitations of the motion control technologies at that time, rather than to satisfy requirements for convenient and economical placement of the equipment imposed by the factory automation. As soon as the advances in the control of industrial manipulators made it possible to move the robotic arms in complex continuous paths, the radial scenario began to restrict the FAB automation and another, "in-line" scenario for equipment arrangement was proposed, and identified as a standard by I300I. Within this scenario the equipment is arranged in an orthogonal manner, which imposes stronger requirements to the motion abilities of the RHS, such as being able to move in arbitrarily situated straight-lines in the Cartesian space, which in turn have to be appropriately blended with the "gross" motions, usually defined in the cylindrical space. The conventional "radial-robots", also called "TRZ-robots" by the names of the participating axes, became deficient in serving "in-line" equipment, with a few exceptions where a radial robot can access "in-line" placed equipment in the so called "skew" manner. The last requires the end-effector to enter the equipment at an angle, but the center of the wafer held by the end-effector still moves in a straight-line coincident with the longitudinal axis of the equipment. However, during the straight-line motion of the center of the wafer, the orientation of the end-effector changes, causing wafer rotation proportional to the length of the straight-line segment. This approach usually works for FOUPs, because they impose fewer constraints on the rotation of the end-effector, and for limited number of process chambers, which allow end-effector rotation during the straight-line motion. If the wafers are required to be placed into differently situated "off-radial" chambers with a prescribed orientation of the notch/flat, they have to be taken with destination dependent angular offsets of the notch/flat from the wafer aligners. The same applies to particular applications that require specific orientation of the wafers when they are placed back into the FOUPs. Another drawback of the "skew" handling is its deficiency to address cases where the end-effector is required to either go into a narrow channel located inside a stage-chuck or in-between closely situated pins inside a process chamber. Current FOUP designs do not allow the edge-gripping end-effectors to completely enter the FOUP in a skew manner, because of

the interferences of the front part of the edge-gripper with the backside of the FOUP. Indeed, this statement might not apply to specially designed edge-grippers, but currently it holds for almost all edge-gripping devices. One possible way to guarantee efficient handling of in-line arranged equipment is to add a degree of freedom (DOF) to the mechanical structure of the robot. Despite the fact that there are a lot of different ways of adding a DOF to a mechanism, only two approaches have been implemented during the last years: (1) placing a radial robot on a linear track, and (2) adding an independently driven axis to the distal end of the kinematic chain of a radial robot. The first approach is straightforward from mechanical and control perspective, but it is quite ineffective since the ratio of the weight of the wafer and the weight of the robot is very small. In order to perform a gross motion, a track-based system carries the heavy TRZ-robot, which in turn creates control difficulties as well as contamination and reliability problems. Space-consumption is another drawback of the "robot on a track" approach. Another, more advanced solution to the in-line handling problem is adding an independently actuated joint, referred to as a "yaw axis" at the end of the TR-structure. The resulting mechanism is stationary, and has enough dexterity to perform a vast variety of motions, including smooth multi-segment trajectories, to optimally address various wafer transfer requirements. After being introduced by Genmark Automation, Inc., in 1997 and patented in 1998 [5], the Yaw-axis concept has become the manipulating core of the majority of the wafer transfer robots for in-line handling - Figure 1.

Figure1. A six-DOF GPR robot with "yaw-axis" capabilities

"Parallel-Series" Manipulating Systems and "Global Positioning Robots" Concept

In many wafer-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 axes orthogonal to the Yaw-axis. 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 wafer matches the orientation of the equipment, and that the wafer stays in one and the same plane while being retracted from the process chamber, the end-effector should have two extra rotations. In 1965, Steward [1] introduced a six DOF closed loop mechanism, known as "The Steward Platform" or "Parallel Manipulator". The interest towards such mechanisms 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 [2], [3]. The advantages of the parallel manipulators over the well-known serial manipulators are their higher accuracy, increased stiffness, better modular design, and simpler inverse kinematics. The limited working area is considered a drawback and that's why the parallel manipulators have been identified as an ideal choice for small and precise fine motions. 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.

Fast Wafer Swap

As discussed above, the fast wafer swap is 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. Similarly to the single arm robots, the dual arm robots can also be placed on linear tracks to serve in-line arranged equipment. 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 2. 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 3.

Figure 2. A fast-swapping robot, capable of handling four 300 mm in-line FOUPs

Figure 3. GPR-SM in motion

Control Systems

As with any mechatronic device the control system of the robots plays significant role in guaranteeing their performance. In the early 1980s, the control systems were still considered a limiting factor in the cooperative work with the mechanics. Regardless of the fact that there were theoretical works dedicated to advanced motion planning and dynamic control of robot-manipulators, the commercial motion controllers were still limited to simple linearly synchronized motions in motor coordinates whose execution was guaranteed by classical PID filters without feedforward compensation. Nowadays, the industrial robot controllers

have advanced significantly, but a great deal of them, especially the ones applicable to wafer handling robots still didn't go beyond the classics. The structural scheme of such a control system is shown in Figure 4.
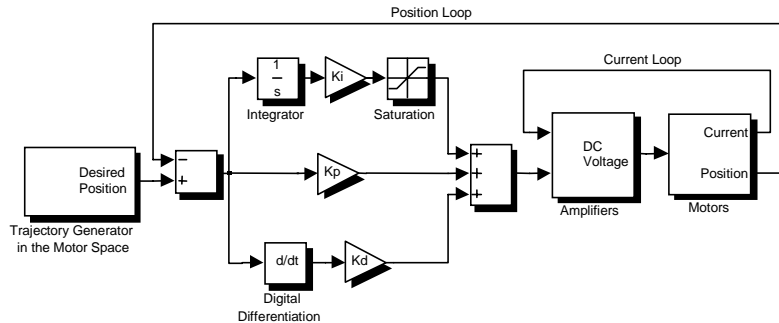

Figure 4. PID filter based control scheme in motor coordinates

The desired position of the multiple axes is calculated by the trajectory generator, and is compared against the current position of the motors, usually measured by the incremental encoders. The output of a conventional PID-filter in analog or PWM form is forwarded to the amplifiers, which in turn supply control voltage to the motors. For the sake of simplicity, all the control schemes in this section are represented in the continuous time domain. Typically, the velocity profiles used in the generation of the desired trajectory are trapezoidal, or are based on parabolic curves. More advanced trajectory generators use polynomial splines of order 3 and higher, B-splines, Bernstein-Bezier Curves, etc.
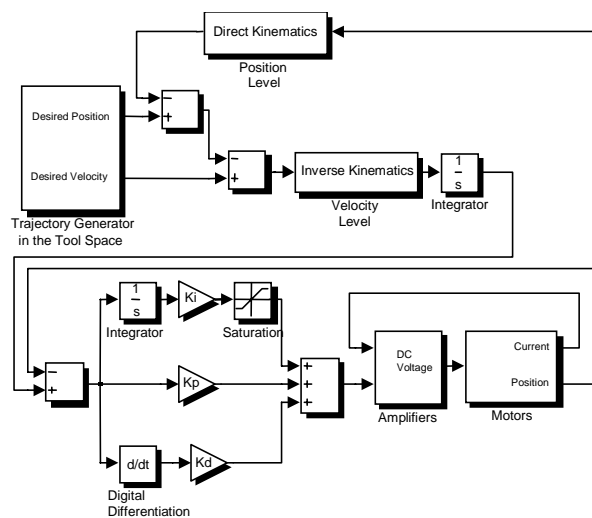

Figure 5: Resolved Motion Rate Control Scheme

The introduction of the Yaw-axis robots has imposed a new requirement to the control systems – the ability to plan the desired motion of the end-effector and to resolve it down to

the joints and the motors via inverse kinematic transformations. The resolved motor positions obtained through digital integration of the reference motor velocities become an input of the PID filter working in the motor space. Being velocity controlled, the servo system is usually not able to guarantee the necessary position tracking accuracy, which in turn requires additional position feedback to be closed around the velocity loop. This approach is known as Resolved Motion Rate Control and was first introduced by D. E. Whitney in 1969 [4]. An exemplary Resolved Motion Rate Control scheme is shown in Figure 5. Most of the PID based motion controllers allow for PID parameters change on the fly but taking the dynamics into consideration is not typical for the RMRC schemes. This requires less computation, but limits the trajectory tracking accuracy and consequently the performance of the RHS.

A reasonable tradeoff between on-line computations and performance is provided by the so-called Resolved Motion Acceleration Control (RMAC) scheme, also known as Computed Torque scheme (Figure 6). This scheme significantly differs from the RMRC. Instead of specifying a commanded velocity at tool level, it calculates the reference acceleration, which is the would-be acceleration of the system that meets the performance objective. The reference acceleration is resolved down to the joint/motor space and together with the current position and estimated velocity is used in the calculation of the desired torque/current. The computation of the desired torque requires the availability of an accurate mathematical model of the controlled arm, the actuators, and the load. The calculations are done on-line, with a frequency that is 5-10 times higher than the natural frequency of the controlled object. A computationally effective scheme based on the Newton-Euler equations of motion and the D'Alembert principle was proposed by Luh, Walker and Paul, 1980 [6].
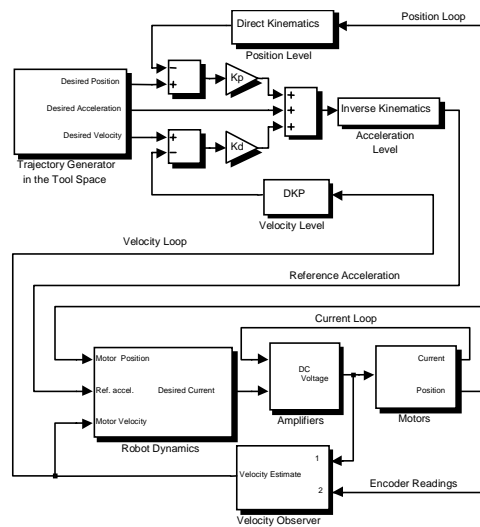

Figure 6: Resolved Motion Acceleration Control Scheme

The RMAC approach is highly recommended for controlling directly actuated robots, because the lack of reduction gears in these robots significantly increases the sensitivity of the control system to load variations due to configuration changes, to external forces and disturbances. The biggest issue within this scheme is the need for accurate mathematical

modeling, which is not always possible. In such cases, it is justified to apply one of the adaptive control schemes applicable to robot-manipulators proposed by Slotine and Li [6] and Krstic et al. [7]. An exemplary adaptive control scheme, based on RMAC is given in Figure. 7. This scheme guarantees boundedness of the tracking error and parameter convergence if persistently exciting trajectories are used as an input.
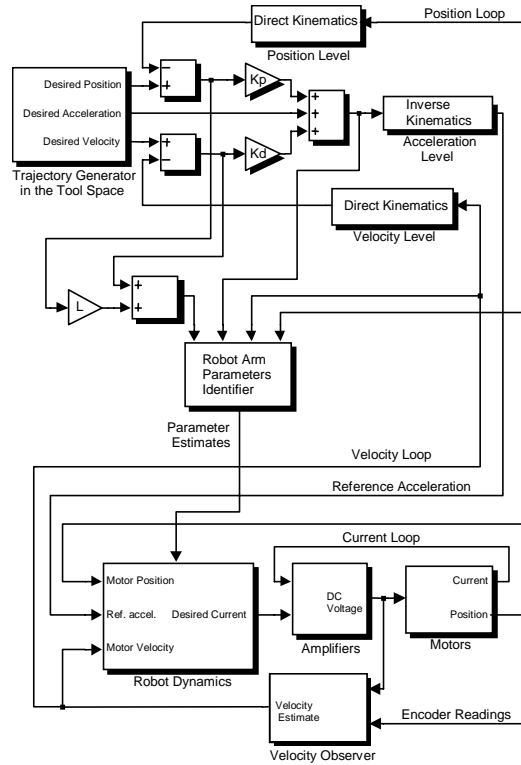

Figure 7. Computed Torque Adaptive Control Scheme with Parameter Estimation

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