Robotic Manipulation of Highly Irregular Shaped Objects: Application to a Robot Crucible Packing System for Semiconductor Manufacture

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Abstract
The basic technology for a robotic system is developed to automate the packing of polycrystalline silicon nuggets into a fragile fused silica crucible in Czochralski (melt pulling) semiconductor wafer production. The highly irregular shapes of the nuggets and the packing constraints make this a difficult and challenging task. To address this task, key research areas are identified, developed, and integrated. In this system, nuggets are grasped by a three-cup suction gripper and manipulated with a seven-degree-of-freedom SCARA manipulator. An optical 3-D vision system, based on active laser triangulation, measures nugget and crucible profiles. A model-free Virtual Trial and Error packing algorithm determines optimal nugget placement in real time. A hybrid position-force control scheme has been implemented and tested for physical nugget placement. The simulation and laboratory tests show that the system has the capabilities of meeting high production rates, achieving high process constraints, and maintaining cost effectiveness that exceed levels obtained with manual packing. The results suggest that model-less robotic sensor control systems can be effective in manufacturing applications. The key contribution of this paper is to show that robot systems can be effectively used to manipulate highly irregular shaped objects in the context of real commercial manufacturing processes.

Keywords: Irregular Object Robot Manipulation, Bin Packing, Semiconductor Manufacturing

1. Introduction
The requirements for growing large, single, device-grade semiconductor crystals are very stringent. Extraordinarily low impurity levels, on the order of 1 part in 10 billion, require careful handling and treatment of the material at each step of the manufacturing process. During the Czochralski (melt pulling) semiconductor wafer production process (also known as the CZ process), highly irregular shaped polycrystalline silicon nuggets

(Figure 1) are packed (charged) into large fused quartz crucibles (Dubowsky 1998; Sujan and Dubowsky 1999; Sujan, Dubowsky, and Ohkami 2000; Sujan and Dubowsky 2000). The nuggets range in weight from a few grams to about 600 grams. Avoiding contamination, protecting the fragile glass crucible from damage, and following complex packing density rules are key constraints during the process (Dubowsky 1998). Once packed, these crucibles are placed in ovens, during which the CZ melt pulling process occurs. The extruded semiconductor ingots are then sliced into wafers from which semiconductor chips are etched. Currently, 45.7 cm diameter crucibles, which are packed manually, are being replaced by much larger (more than 91.5 cm diameter) crucibles for use in the upcoming fabrica-
tion of a new generation of 300 mm diameter wafers (Dubowsky 1998). For these larger crucibles, manual packing is neither ergonomic nor practical. Automation has the potential benefit of reducing cost, achieving greater packing consistency, and reducing packing time. Previous studies have concluded that because each nugget has unique size and shape, and because packing rules are so strict, fixed automation was not feasible (Dubowsky 1998). Additionally, studies also show that process modification, such as nugget crushing and pouring, results in reduced yields (Dubowsky 1998). The objective of this study was to develop a more flexible robotic system to automate the crucible packing process. This paper describes the system.

The large variance in size and weight, the irregular shape of the nuggets (see Figure 1), and the strict process requirements result in four key technical challenges to automate the crucible packing process with a robotic system. First, the nuggets are difficult to grasp. Second, nuggets must be placed in accordance with their geometry and the proper set of packing rules within the process specifications; hence, each nugget and crucible surface must be scanned rapidly and accurately to get surface profiles before a nugget is placed. Third, the planning system must use this profile information to determine the optimal placement of a nugget in a crucible. Determining the best location to place each nugget is necessary due to the importance of the packing density and complex process constraints. Finally, the irregularly shaped and stiff nuggets must be carefully placed against the fragile quartz crucible wall without scratching and contaminating the process. They must also be carefully placed against other nuggets in the process without disturbing the existing structure. This is usually accomplished by handling the larger nuggets individually.

Systems in which robotic manipulators are used to pack irregularly shaped objects have been considered for the food handling industry and for the bin picking problem (Neal, Rowland, and Neal 1997; Trobina and Leonardis 1995). These systems have considered some of the challenges addressed here; their capabilities are unable to meet the requirements set by the semiconductor production process. Figure 2 shows a schematic of a packed crucible. The packing rules are set by the technology and the stringent traditional CZ crystal production rules. These packing rules require that the nuggets are packed in layers. Packing is initiated with a bed layer formed by smaller, gravel-sized nuggets. Subsequent nugget layers consist of larger wall nuggets and internal smaller bulk nuggets. Alternate filling of the bulk and wall nuggets eventually provides a full crucible. Finally, packing is completed with a crown of larger nuggets. Figure 3 shows the system concept developed in this study. During the stratified packing, nuggets are acquired one at a time by the manipulator and passed over the nugget scanner to obtain the surface profile. Simultaneously, the crucible surface profile is mapped by an overhead vision system. A packing algorithm applies this vision data to compute an ideal position for the nugget. The rules to determine this location are described in section 5.

This study showed that the concept could pack crucibles at a higher rate than manual packing, provide better consistency, and eliminate the need for
the operator to perform a physically tedious and unpleasant job (Dubowsky 1998). The analysis suggests that a return on investment of less than two years could be achieved under full operating conditions. This paper describes the design, integration, and calibration of the grasping/manipulation, vision, placement planning, and control systems for the robot-assisted crucible packing system. A gripper, based on vacuum forces for grasping, coupled with a four-degree-of-freedom Adept-1 manipulator and three-degree-of-freedom wrist, manipulates the nuggets is described. Two 3-D vision systems using active laser triangulation with CCD cameras map the crucible and nugget surfaces. An online model-free packing algorithm determines the placement of 3-D irregular nuggets in process constraints and limitations. Using a cost function to determine nugget placement, complex packing rules and constraints of the CZ process can be readily included in the packing algorithm. Finally, a hybrid position/force control algorithm is developed and implemented for regulating the delicate contact forces while in contact with a stiff and fragile environment. Experimental results (sections 3-7) and economic analysis (section 2) show the system can meet the requirements for automation of the CZ process. The details of the system design, the individual subsystems, and the integrated system are presented in the following sections. Additionally, a literature review of related work on each subsystem is also provided. Section 2 reviews the overall system and presents its economic viability, section 3 covers the design of the grasping and manipulation system, and section 4 describes the vision systems. Section 5 presents the nugget placement planning algorithm, section 6 presents the hybrid control architecture of the manipulation system, and section 7 addresses the full system integration.

2. Overall System Design

Figure 4 shows the factory system with this one custom-made, SCARA robot. The crucible is brought into position by a conveyor belt and mounted on a support structure, which accurately locates it relative to the overhead surface mapping system. The system operator removes the nuggets from the sealed bags, sorts them into large nuggets (weight greater than 60 grams) and small nuggets or bulk fill, and places the sorted nuggets onto a conveyor system (see Figure 4). There is a separate conveyor for the large nuggets and the small nuggets. One operator sorts nuggets for two robotic filling stations. Each robot has its own small and large nugget conveyor system. At the far end of the large nugget conveyor is a target sensor, where the nugget is picked up by the robot. The small nuggets are conveyed to two filler bins that are picked up and emptied into the crucible.

The system timing is critical to the economic viability of the system. It takes approximately 6 seconds to pick up the filler bin and empty a bulk fill container (smooth spreading the fill). For each of the larger nuggets, it takes a total of 8½ seconds for the manipulator to pick up the nugget, pass the nugget to and over the nugget mapping system, place it in the crucible, and return to the nugget pickup location.

To minimize the packing time, the portion of the packed surface that has recently been worked on is scanned while the manipulator is away from the crucible picking up and scanning the next nugget. This local high-resolution (1 mm) scanning is a rectangular area 6 inches in width and 36 inches in length. An entire crucible scan at a low resolution (1.5 cm) is performed after every 10th nugget placement to account for unexpected motions/disturbances of nuggets. The crucible pack and nugget surface maps are used to plan the optimal location for the nugget while the robot is moving the nugget to the crucible. A timing diagram for the packing of the 36 inch diameter crucible is shown in Figure 5.
3. Grasping/Manipulation System

3.1 System Requirements and Design

The irregular silicon nuggets can be qualitatively divided according to surface shape and quality. Some nuggets have a characteristic mottled surface texture, while others display especially jagged angles. For successful grasping and manipulation, the gripper must be able to grasp at least 85% of the large (80 grams and above) nuggets, grasp the bulk filling bin, and orient nuggets through ±180° yaw and ±15° pitch and roll for arbitrary nugget-wall contact.

Mechanical gripper designs considered in this study can be grouped into four classes: clamping grippers, universal grippers, specialty grippers, and vacuum/magnetic grippers (Fan Yu 1982, Wright and Cutkosky 1985). Universal grippers are designed to grasp a variety of parts without reconfiguration of the gripper (Mason 1985, Perovskii 1986). Both universal and clamping grippers must grasp objects using opposed surfaces. Specialty grippers are often application specific—typically a customized tool. Vacuum and magnetic grippers can pick up parts using one object face; however, magnetic grippers can only lift ferric materials and hence are not appropriate for silicon nuggets. Vacuum grippers, although promising for their inherent grasping compliance, have been applied toward irregular objects in only a limited number of cases (Manna, Akvurt, and El-Kalay 1991); however, in this study it was found that a vacuum gripper could be designed to handle the highly irregular shaped nuggets and meet the system constraints.

In developing the vacuum gripper, determining the vacuum cup material, size, shape, number, and configuration are key design parameters. The vacuum cup material is selected based on contamination constraints. Vacuum cup size, shape, and number determine the maximum lifting force for a given pressure gradient; however, due to the highly irregular shapes of the nuggets, perfect seals are hard to obtain. Hence, vacuum cup geometry must be determined empirically. Vacuum cup geometry can be described using four criteria: the presence of cleats, the shape of the lip, the depth, and the compliance of the vacuum cup. Nugget grasping tests indicate that a bellowed, sharp-lipped, nonshallow, smaller vacuum cup is the optimum cup.

The gripper features three closely spaced FDA-grade vinyl B3-1 vacuum cups mounted on a mani-
fold plate (Figures 6 and 7). This material was found to be least likely to contaminate the packing process. A single vacuum line enters the manifold. Flow to each of the cups is regulated by three restriction valves in the manifold. Without flow restriction, a single unsealed cup would result in power (pressure) loss to the other cups. A pressure transducer added to the pneumatic lines measures the vacuum pressure at a point just before the manifold. A successful grasp can then be identified.

The wrist developed to support the gripper is capable of $\pm 30^\circ$–$60^\circ$ pitch, $\pm 90^\circ$ roll, and continuous yaw rotation. Coupled with a four-degree-of-freedom Adept 1 manipulator, the seven-degree-of-freedom system allows for arbitrary nugget placement with respect to the crucible. The six-axis force/torque sensor (see Figure 7) is used for force control in manipulating the grasped nugget against the crucible wall and previously placed nuggets (see section 6).

3.2 Experimental Validation

To tune the manifold pressure for a successful grasp, a calibration set of 20 nuggets was selected. A successful grasp required only two successful cup seals. A maximum downward force of 15 N was used, at which point the vacuum cups would bottom out. The flow resistance for a cup was tuned by sealing two cups and adjusting the restriction valve of the open cup until the desired manifold pressure was reached. Figure 8 shows the number of the nuggets successfully grasped as a function of manifold pressure, for both the two-cup and three-cup seal. The greatest number of nuggets was grasped at a vacuum pressure of .76 atmospheres.

For low manifold pressures (low flow resistance), grasping was unsuccessful in the two-cup trials because the unsealed vacuum cup power loss prevented enough pressure from being applied to the nuggets. For the three-cup trials at low pressure, the higher air flow enhanced the ability of three cups to seal onto very rough surfaces of nuggets. At higher manifold pressures, the grasping performance for the three-cup gripper fell due to low air flow, decreasing sealing ability. Once calibrated for optimum manifold pressure, the gripper grasped 90.9% of all nuggets in one attempt and 98.1% in two grasping attempts.
4. 3-D Vision System

4.1 System Requirements and Design

The two vision systems provide, respectively, the 3-D surface geometry of the individual nuggets and of the surface of nuggets already in the crucible. The requirements for the nugget mapping system are: $X$, $Y$, $Z$ resolution of 1 mm and a mapping time of 2-3 seconds. The requirements for crucible surface mapping system are: $X$, $Y$, $Z$ resolution of 1 mm and a mapping time of about 4-5 seconds. It must also be able to look down from a position that does not interfere with the manipulator (Sujan and Dubowsky 1999).

The CZ process contains constraints, such as a complex environment, cost, and compactness, which make the practical design of 3-D surface geometry measurements very challenging. A number of methods to obtain visual 3-D data of an object were considered, including triangulation methods, holographic interferometry (phase shift measurement), radar (time of flight), lens focus, and Moiré techniques (Besl 1989, Hsueh and Antonsson 1992, Jarvis 1983). All these methods suffer some limitations, such as blind regions, computational complexity, limited to highly textured or structured scenes, limited surface orientation, and/or limited spatial resolution (Jarvis 1983). For this system, laser triangulation was selected as being most effective.

Laser triangulation can be achieved by a single camera aligned along a $Z$-axis with the center of the front node of the lens located at $(0,0,0)$ giving the origin of the camera coordinate frame (see Figure 9). At a baseline distance $b$ to the left of the camera (along the negative $X$-axis), a laser projects a plane of light at an angle $\alpha$ relative to the $X$-axis baseline. The point $(x, y, z)$ in the scene is projected onto the digitized image at the pixel $(u, v)$, controlled by the focal length of the lens, $f$. The measured quantities $(u, v)$ are used to compute the 3-D coordinates $(x, y, z)$ of the illuminated scene point:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \frac{b}{f \cdot \cot(\alpha) - u} \begin{bmatrix} u \\ v \\ f \end{bmatrix}$$

(1)

The $X$ and $Y$ resolution ($\delta X$, $\delta Y$) is given by the width of the projected image onto the detector divided by detector resolution. The depth resolution ($\delta Z$), given image width $W$ and detector grid size $n$ in pixels, is given by:

$$\delta Z = \frac{(W \tan \alpha)}{n}$$

(2)

Based on the requirements, the crucible and the mapping systems shown in Figures 10 and 11 were developed. A low-resolution global scan of the 45.7 cm diameter crucible with $XY$ resolution of 1.5 cm takes one second to process. A high-resolution local scan (15 cm wide band) with $XY$ resolution of 1 mm takes 4.5 seconds to process. Laser scanner times are negligible. The nugget mapping system consists of a fixed laser and camera over which the manipulator passes the nugget at a constant speed of 3 cm/s. Careful synchronization of the manipulator motion and the mapping system are required. A nominal nugget (7.5 cm x 7.5 cm) takes 2.5 seconds with an $XY$ resolution of 1 mm, based on a video frame rate of 30 frames/second. Critical parameters for both systems (such as inter camera-laser distances, camera field of view, incident laser angles, etc.) can be determined from a trade-off study between the system requirements.

4.2 Calibration

Imperfections in the lens or the detector can result in image distortions. Intrinsic camera calibration maps the errors in image plane coordinates $(u, v)$ and then uses this to compensate the measured values to produce accuracy equal to the resolution of the system. The process for intrinsic calibration has been adapted from Hsueh and Antonsson (1992). Given a known horizontal incident angle $\gamma$ and vertical incident angle $\beta$ between the light ray and the principal axis, and a known principal distance $f$, the “expected” image plane coordinate $(u, v)$ can be cal-
culated. Subtracting these from their actual values gives the error map value.

\[ u_{\text{expected}} = f \cdot \tan \gamma, \quad v_{\text{expected}} = f \cdot \tan \beta \]  
(3)

\[ E_u = u_{\text{expected}} - u_{\text{measured}} = f \cdot \tan \gamma - u_{\text{measured}} \]  
(4)

\[ E_v = v_{\text{expected}} - v_{\text{measured}} = f \cdot \tan \beta - v_{\text{measured}} \]  
(5)

This scheme assumes that \( E_u \) at \( \gamma = 0 \) and \( E_v \) at \( \beta = 0 \) are 0. For nonideal lenses the focal length, \( f \), would have to be mapped as an average value given by Hsueh and Antonsson (1992):

\[ f \approx \bar{f} = \frac{1}{n} \sum_{\gamma} \frac{u_{\text{measured}}}{\tan \gamma} \]  
(6)

Using binary interpolation, an \( E_u \) and \( E_v \), can be looked up for every \((u, v)\) pair, and compensations made.

Also, in practice, the extrinsic parameters of the system, such as lens focal length \( f \), inter camera-laser distance \( b \), and mounting geometry with respect to the ground, are not well known, and need to be calculated. By scanning a known object at two known scan angles, six independent equations in six vari-

\[
\begin{align*}
    l &= \frac{g}{\sin \alpha} \\
    b &= z \cdot \cot \alpha \\
    b &= b' - l \cdot \cos \alpha \\
    z^2 + b^2 &= r^2 \\
    \frac{\sin(\beta - \alpha)}{\partial h} &= \frac{\sin(\gamma - \beta)}{r + l} \\
    \frac{\sin(\pi - \beta)}{l} &= \frac{\sin(\beta - \alpha)}{x}
\end{align*}
\]  
(7-12)
where $g$ (measurable), $\alpha$, $\beta$ (predefined scan angles), and $\delta h$ (object height) are known. The variable $x$ is defined as the distance between the intersection points of the two incident rays, at angles $\alpha$ and $\beta$, with the extended camera lens front nodal plane. These equations are solved for multiple measured height pairs and averaged to obtain solutions for the extrinsic variables.

### 4.3 Experimental Validation

In mapping the nugget field inside the crucible, a 15 KHz data acquisition rate is obtained, given a video rate of 30 frames per second and CCD resolution of 500 x 500 pixels on a Pentium 166 MHz system (see Figures 13 and 14). This yields a mapping time of 4.5 seconds for 45.7 cm diameter crucible with 1 mm resolution. Low-cost improvements in resolution and computational speeds of the crucible mapping system hardware can substantially increase this data acquisition rate. The precise measurement of a nugget field to check the crucible mapping system accuracy is difficult; however, estimates of the systems precision indicate that the crucible mapping system meets the required specifications. These estimates were achieved by mapping a known flat surface.

The nugget mapping system was evaluated using representative nuggets. Nugget mapping of a characteristic dimension of 7.5 cm and 1 mm resolution takes 2.5 seconds based on the 15 KHz data acquisition rate. Nugget maps generated were compared with nugget profiles obtained from a coordinate measuring machine. The RMS error between the profiles generated by the two systems is 0.4 mm with $\sigma$ of 0.2 mm (the accuracy requirement is $\pm$1.0 mm) (Sujan and Dubowsky 1999).

### 5. Placement Planning

#### 5.1 Packing Algorithm Requirements and Design

The crucible is packed in a stratified manner by alternating between placing large nuggets at the wall and center bulk placement, finished with a crown (see Figure 2). The packing algorithm must determine where a nugget is placed meeting a set of packing rules, minimizing nugget rejection, and optimizing the charge density profile. Data provided to the packing algorithm consists of the $[x,y,z]$ maps of the nugget surface and the packed surface. To meet packing rate results, a processing time of one second on the control computer is required to determine a nugget position.

Previous work in 2-D and 3-D packing have been largely focused on structured objects such as rectangles or rectangular solids, respectively (Cheng and Penkar 1995, Coffman and Shor 1993, Dubowsky 1998). The algorithms developed are largely off-line or online processing (Coffman and Shor 1993, Dubowsky 1998). To solve the off-line problem, a number of algorithms have been proposed, including dynamic programming, branch-and-bound searching, and heuristic search techniques (Coffman and Shor 1993, Dubowsky 1998, Li and Cheng 1992). While they have been shown to produce near-optimal solutions, they are at best pseudo-exhaustive in nature, computationally intensive, and impractical when the number of objects to be packed is large. Online algorithms, such as genetic algorithms, model-based fit-
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A global packing strategy may be one or a combination of several of the above rule primitives. For the CZ packing process, additional packing rules, such as crucible-nugget contact requirements and variable-density packing through the charge, can be added directly to the packing strategy. A series of packing strategies were defined and simulations were used to determine the best strategy. Their performance was evaluated based on charge density, the number of nuggets packed successfully out of the number presented, and the stability of their placement. The performance index (PI) to evaluate the cost function is defined as:

\[
P.I. = \frac{d \cdot N_2}{\sigma \cdot N_1}
\]

where \(d\) is the mean charge density, \(N_1\) is the number of nuggets presented, \(N_2\) is the number of nuggets packed, and \(\sigma\) is a measure of stability. Although each individual nugget may be in a locally stable position, the global pack may be unstable, much like a house of cards (see Figure 16). To deal with this issue, a global stability metric is defined. Figures 16a and 17a show the frequency of a given height variation during packing about the current mean height calculated. A narrow range of variations reflects a more stable and stratified pack. The algorithm limits the maximum height above the lowest point on the crucible surface profile to which a nugget can be placed.

### 5.2 Packing Results

A number of cost functions were studied in simulation to evaluate their effectiveness in giving an optimal pack. Initial simulations were done in 2-D with six cost functions formed from the above packing rule primitives. These include (a) lowest fit, (b) lowest fit with the minimum excess area, (c) first fit, (d) lowest first fit, (e) minimized area fit, and (f) minimized area fit weighted by contact fit. The nugget shapes are approximated by random nonconvex polygons where the size distribution was based on measured nugget data (Dubowsky 1998, Sujan and Dubowsky 2000). Table 1 shows the results for the random distribution of nonconvex polygons. It can be seen that the case of lowest-fit packing has the best performance index for both the polygonal and rectangular object packing among the cost functions considered. The lowest-fit method, unlike the other methods, does not require the explicit use of the height-limiting parameter, as the function implicitly causes uniform stratified packing. This
helps reduce the percentage of rejected objects and provides for a more “natural” packing structure.

In a 3-D simulation, the nugget shapes are approximated by random polyhedrons. Simulation results for packing the walls and crown of the 45.7 cm and 91.4 cm diameter crucible yielded an average charge density of 48% and 57.5%, respectively (with $\pm 15^\circ$ wrist rotations in pitch and roll) using the lowest-fit packing rule. With bulk filling, the charge density increases to 50% and 60%, respectively. It has been suggested that a controlled variable density through the crucible can improve product quality. The use of this robotic system should provide the consistency to permit this question to be addressed quantitatively. Computational speeds for placement planning are within the 1.0 second per nugget requirement using a PC with a Pentium 166 MHz processor. Further, object shape and geometry are not influencing factors in the performance of the algorithm.

### Table 1

<table>
<thead>
<tr>
<th>Packing Scheme for Random Polygons</th>
<th>Mean Charge</th>
<th>Number of Objects Presented</th>
<th>Number of Objects Packed</th>
<th>Stability: Standard Deviation About Reference (units $\delta_h$)</th>
<th>Performance Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>$N_1$</td>
<td>$N_2$</td>
<td>$\sigma$</td>
<td>$(d \cdot N_2/N_1)/\sigma$</td>
<td></td>
</tr>
<tr>
<td>Lowest fit</td>
<td>75.72 (79.22)</td>
<td>206</td>
<td>204</td>
<td>5.663</td>
<td>13.245</td>
</tr>
<tr>
<td>Lowest fit w/ area minimization</td>
<td>75.37 (78.93)</td>
<td>207</td>
<td>203</td>
<td>6.4583</td>
<td>11.442</td>
</tr>
<tr>
<td>First fit</td>
<td>66.05 (69.25)</td>
<td>225</td>
<td>175</td>
<td>18.0159</td>
<td>2.851</td>
</tr>
<tr>
<td>Lowest first fit</td>
<td>65.78 (68.9)</td>
<td>241</td>
<td>173</td>
<td>16.7</td>
<td>2.872</td>
</tr>
<tr>
<td>Excess area minimization</td>
<td>75.83 (79.26)</td>
<td>232</td>
<td>204</td>
<td>11.3769</td>
<td>5.862</td>
</tr>
<tr>
<td>Excess area minimization with contact fit</td>
<td>73.88 (76.91)</td>
<td>228</td>
<td>200</td>
<td>14.6023</td>
<td>4.439</td>
</tr>
</tbody>
</table>

### Wall and crown building

- Nugget to crucible wall $< 30$ cm/s; contact force while sliding nugget $< 5$ N

### Bulk filling

- Bulk filler approaches crucible in 2.5 seconds; filler shaken at 4 Hz with $2^\circ$ amplitude

The wall and crown building mode is a challenging control mode. Difficulties arise when the nugget comes into contact with previously placed nuggets. Hence, this section will briefly discuss this aspect of the control. An algorithm must be used that can regulate force and position without a priori information on the surface orientation. To achieve the combined force and position control required during this mode, the well-known hybrid force/position control was selected (Dubowsky 1998).

Two major approaches for both contact force and endpoint position control for manipulators are the hybrid position/force control and impedance control (Craig 1989). In hybrid position/force control, perfect position tracking can be obtained without the generation of excessive contact forces, making it highly applicable to known stiff environments (Raibert and Craig 1981); however, switching position and force domains during contact can cause instability. Various schemes have been devised that incorporate sensor information to achieve improved endpoint position and force control without introducing the system instabilities (Li 1996, Muto and Shimokura 1993). Impedance control employs a dynamic model to create equations of motion of a manipulator (Hogan 1984). When contact force feedback is incorporated in the model, force control can be achieved. The advantage of impedance control is its stability and applicability during the entire contact control task; however, this leads to large position errors. Hence, the hybrid control was selected.

### 6. Control System

#### 6.1 Control System Requirements and Design

Crucible charging involves five distinct subtasks for the control system: nugget acquisition, nugget scanning, slew motion of nugget to crucible, wall and crown building, and bulk filling. Most of the manipulator actions can be accomplished quite well with conventional position control. The requirements are:

- **Nugget acquisition**—vertical motion at 15 cm/s; maximum vertical force of 15 N
- **Nugget scanning**—horizontal motion at 3 cm/s; maximum position error of 0.5 mm
- **Slew motion**—nugget brought to crucible in 2.5 seconds
Two hybrid position/force control schemes have been implemented and tested. One performs Jacobian Transpose control in the position domain; the other performs Jacobian Inverse control in the position domain. Both schemes perform Jacobian Transpose control in the force domain.

Figure 18 shows the implemented Jacobian Transpose hybrid position/force control algorithm. The position domain and force domain are represented by the projection matrix P and the complementary projection matrix F, respectively. The joint locations q are measured and converted via the kinematic equations (Kin) to endpoint position x. The gains $K_p$, $K_d$, and $K_v$ represent stiffness, damping, and integration gain in the Cartesian task-space. A Jacobian Inverse position control algorithm can also be structured.

It is important to minimize the approach speed so that there is no impact damage to the crucible. It is possible that the manipulator loses contact, and this condition must be handled gracefully by prohibiting the manipulator to achieve high speeds. If the manipulator breaks contact, the integral force controller shown in Figure 18 is replaced by a velocity damping term and an integral positioning term, which brings the manipulator back into contact with the surface slowly.

It is important to note that the P and F selection matrices are likely to change during a contact control task. Before contact, P is the identity matrix (full rank) and F is the zero matrix (no rank). After point contact without friction, the P matrix loses one rank and the F matrix gains one rank; however, due to the integrator locations as shown in Figure 18 a discontinuous change in P and F does not translate to a large discontinuity in control input.

6.2 Results

To demonstrate the effectiveness of both Jacobian Inverse and Jacobian Transpose based algorithms, two-dimensional simulations were performed. The system model consists of a SCARA manipulator arm in contact with a stiff cylindrical crucible. Figure 19 shows the results of one simulation. Here the end effector moves under pure position control ($P = I, F = 0$) with a speed of 0.33 m/s in the $-y$ direction until contact is made with the crucible. Once contact is detected, the system switches selection matrices so that there is position control in the $x$ direction and force control in the $y$ direction. Figure 19 shows the results of an experiment in which the end effector is held fixed after contact and the contact force is commanded to be regulated at 15 N. While this is much higher than required for the packing problem, it tends to reveal any enhanced impact problems on contact. Contact
is detected at 4.5 seconds and results in a substantial (but reasonable) initial force spike and oscillation, quickly regulated to 15 N. There is a momentary positioning error.

The control system design was also studied experimentally. Figure 20 shows the experimental system. Figure 21 shows representative results in which the nugget is held fixed against the vertical wall. Once contact is detected, the force profile oscillates for several seconds and settles on the chosen value of 5 N, which was experimentally determined to be low enough to avoid scratching the glass. Deviations of approximately 0.5 N are the result of sensor noise. The z-positioning error was very small in this example (less than 0.02 mm) because the system was acting as a regulator in this direction, and the dynamics of the prismatic joint (z-direction) are decoupled from that of the rest of the manipulator system.

Figure 22 shows the results of a trial in which the nugget is commanded to slide in the vertical (z) direction while in contact with the wall. The desired contact force is set at 5 N to avoid surface scratching. The desired position trajectory is a 0.1 Hz sinusoid of amplitude 1 cm. Contact is detected at approximately one second. The force controller is partly able to maintain the desired force, with deviations ranging from +1 N to −2.5 N. The position controller maintains the vertical position error to within ±2 mm.

The experimental results show that the implemented hybrid position/force control algorithms perform well when the position controller acts as a regulator, and show some success with simultaneous motion and force profiles. In cases where the robot loses contact with the surface, contact is reestablished safely.

Experimental results suggest that several factors influence the degradation of the controller when generating simultaneous position and force profiles: dynamic coupling in the force/position domains, force sensor cross-talk, joint friction, and oversimplification of the model. To obtain better performance with a hybrid controller, elimination of these disturbances is required. A friction compensation scheme such as BSC control has been shown to remove many of these effects (Morel and Dubowsky 1996). A complete discussion of this approach and its applications to contact problems is beyond the scope of this paper.

7. Laboratory System Integration

The laboratory system consists of a robot manipulator and control system, vision/packing system, and wrist/gripper system (see Figure 23). The packing procedure plays a supervisory role in planning and assigning control to the major subsystems. This includes nugget acquisition, nugget scanning, crucible surface mapping, placement planning, nugget placement, and bulk filling.

To provide for accurate scheduling, the governing system communicates with the four major subsystems, either across computers or across programs. It is recommended that a factory-level system be operated by a central workstation to maintain simplicity. For intercomputer communication, a series of asynchronous handshaking protocols have been developed for communication. These include:

- Trigger nugget mapping module for nugget scan
- Trigger crucible mapping module for crucible surface profiling
The system was implemented and tested on a 166 MHz Pentium computer, using the C++ programming language. The control code is interrupt-driven. The computer system multitasks between two programs: a slow outer loop (which handles subsystem task scheduling and interaction of the system with the user), and a faster time-critical inner control loop (which processes the encoder information and produces an output control commands for the manipulator/gripper and the vision systems). Information is passed between the two loops via data latching and semaphore. Because the outer loop can be interrupted at any time, including while writing data to memory, it is necessary to set up strict guidelines about the validity of data being transferred between the two programs. This is an added complication inherent in multitasking or parallel processing.

Because the crucible charging environment can be damaged rather easily, it is very important to allow user interaction to alter the manipulator's behavior online. The system was able to pack nuggets at an average rate of one nugget every 10 seconds, reaching a charge density of 50% for the 45.7 cm diameter crucibles, allowing the system to stay competitive with human packing.

8. Conclusions

The technology has been developed to enable the robotic packing of crucibles in CZ semiconductor wafer production. Benefits of the system include elimination of nonergonomic working conditions, shorter crucible packing times, greater crucible packing consistency, and higher productivity and reduced costs. The design includes the development of a gripper mechanism, nugget and crucible surface mapping modules, a nugget packing algorithm, and control of a manipulator with sufficient compliance and accuracy in the delicate placement of the nugget.

The results of the grasping tests indicate that the designed gripper can perform its required task effectively, with a 98% grasping success. Nugget manipulation is attained with a four-degree-of-freedom SCARA-type manipulator and a three-degree-of-freedom wrist. The noncontact 3-D geometry measuring system based on active triangulation measures both the nugget geometry profile and the internal crucible geometry profile, with a resolution of 1 mm and scanning times of 2.5 seconds and 4.5 seconds, respectively. A Virtual Trial and Error packing algorithm is developed and tested in simulation for cost function optimization. The final packing algorithm has been applied in simulation and a charge density of 60% for the 91.4 cm diameter crucible is achieved. This compares well with the expected performance of human packing. A hybrid position-force control scheme has been implemented and tested for physical nugget placement. Promising results for simultaneous motion and force profiles have been obtained. The integrated system has been shown to achieve charge densities of about 50% for 45.7 cm diameter crucibles. Required precision and cost effectiveness has been demonstrated. The results suggest that model-less robotic sensor control systems can be effective in manufacturing applications.

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References


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Steven Dubowsky received his bachelor’s degree from Rensselaer Polytechnic Institute in 1963 and his MS and ScD degrees from Columbia University in 1964 and 1971. He is currently a professor of mechanical engineering at MIT. He has been a professor of engineering and applied science at the University of California, Los Angeles, a visiting professor at Cambridge University, Cambridge, England, and a visiting professor at the California Institute of Technology. During the period from 1963 to 1971, he was employed by the Perkin-Elmer Corporation, the General Dynamics Corporation, and the American Electric Power Service Corporation. Dr. Dubowsky’s research has included the development of modeling techniques for manipulator flexibility and the development of optimal and self-learning adaptive control procedures for rigid and flexible robotic manipulators. He has authored or coauthored nearly 100 papers in the area of the dynamics, control, and design of high-performance mechanical and electromechanical systems. Professor Dubowsky is a registered professional engineer in the state of California and has served as an advisor to the National Science Foundation, the National Academy of Science/Engineering, the Dept. of Energy, and the US Army. He has been elected a fellow of the ASME and is a member of Sigma Xi and Tau Beta Pi.

Yoshiaki Ohkami obtained his PhD in engineering from the Tokyo Institute of Technology in 1968 and joined the National Aerospace Laboratory of Japan as a research engineer on spacecraft attitude control and large space systems (1968-1992). From 1972-74, he worked as a visiting researcher at the University of California at Los Angeles (UCLA) as a NASA International Fellow. From 1985-1986, he was the deputy director for the Space Station Program Office at the Science and Technology Agency. From 1992-2000, he was a professor at the Tokyo Institute of Technology Dept. of Mechatro-Aerospace Engineering. He is currently the special advisor to the president at the National Space Development Agency (NASDA) of Japan. Major fields of research are dynamics and control of large space systems, space robotics, and distributed control with computer networking. He is a member of IEEE, the American Institute for Aeronautics and Astronautics, the Japan Society of Mechanical Engineers, the Japan Society for Aeronautical and Space Sciences, and the Robotics Society of Japan.