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Automatic dextrous microhandling based on a 6 DOF microgripper

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Abstract

The demand for automatic quality inspection of individual micro components increases strongly in micro optoelectronics industry. In many cases, quality inspection of those micro components needs dextrous microhandling. However, automatic dextrous handling of micro components is a very challenging issue which is barely explored. This paper presents a high-DOF (degrees of freedom) automatic dextrous handling and inspection system for micro optoelectronic components using a novel 6-DOF piezoelectric microgripper. The control system includes three hierarchical layers: actuator control layer, motion planning layer, and mission control layer. Machine vision is applied in automatic manipulation. The performance of the system is demonstrated in a vision based automatic inspection task for $300 \times 300 \times 100 \mu\text{m}$ sized optoelectronics components and reached a cycle time of $7.1 \pm 0.3\text{s}$.

Keywords: dextrous microhandling; 6-DOF microgripper; automatic manipulation; vision based inspection.

1. Introduction

Microhandling refers to operation of micro-objects (objects that are smaller than 1 mm). A microhandling system can be a manually operated device or an automatically controlled instrument. Early microhandling was carried out by manual instruments. Robotic based microhandling was not widely researched until late 1980s. Since then, many prototypes of micromanipulators have been reported for different applications [1-24]. Different actuation principles have been applied, including piezoelectric, electrostatic, electromagnetic and shape memory alloy actuators. Applications of microhandling lie in the areas such as microassembly, microsurgery, and various biotechnology operations. For example, microhandling has been applied in assembly of microrobotic structures [16-18, 25] and MEMS components [9, 22, 26]; minimally invasive examination and surgery [27]; minimally invasive microhandling of microbe [20]; intra-cytoplasmic sperm injection [28]; ophthalmic surgery [29]; manipulation of DNA [30, 31]; manipulation of carbon nanotube [32]; manipulation of micro particles [10].

Microhandling can be carried out by contact methods, mostly mechanical [2, 4, 7, 9, 13, 16, 18, 22-26], or various non-contact methods such as optical pressure [1, 3, 12, 20], acoustic and ultrasonic wave [10, 33-35], magnetic field [18, 36], electrical field [21], or a combination of several methods. The environment of microhandling can be air, liquid or vacuum (often in an

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SEM). Many microhandling and assembly applications are carried out in air [9, 13, 16-18, 22], sometimes in vacuum [15, 23, 32, 37] or liquid [38, 39]. Biological applications are often carried out in liquid, e.g. [20]. Contact methods are the mostly used methods for microhandling in air or vacuum (e.g. [9, 16, 22-18, 32]), while mechanical contact methods usually are the first choices considered in many applications. The major advantage of microhandling by contact methods is the freedom of applying different actuation principles and robotic systems. Consequently, the workspace and degrees of freedom are limited only by the robotic systems or the actuation systems. In applications such as biological handling operations, contact manipulation is not preferred due to possibility of damaging the objects. Laser-trapping based microhandling and other non-contact principles are often applied in those applications [12]. Other field-based manipulation methods, such as magnetic field, electrical field, dielectrophoretic transportation and ultrasonic systems, normally have less degree of freedom and are often used in applications not requiring precise control of position or in applications having confined workspaces such as surfaces. Despite of its wide applications in biotechnology, laser trapping and other non-contact type microhandling is rarely applied in other microhandling and microassembly applications.

For contact microhandling, many types of end-effectors are used in different micromanipulation systems, ranging from needles, pipettes, and microgrippers to special tools such as micro knives. A needle is the simplest type of end-effector. Glass pipette can be pulled to create a pipette tip in sub-micron diameter, which is the most widely used end-effector in biomanipulation and other biotechnological applications. Glass and metallic pipettes can also be used as end-effectors in vacuum microgrippers [40]. On the other hand, microgrippers are the most widely used end-effectors in applications other than biotechnology.

A microgripper can handle objects by applying force mechanically using various actuators [41]; or handle objects by other techniques, such as vacuum [40, 42], electrostatic force [43, 44], capillary force [45, 46], ice [47] and airflow (Benoulli effect) [48]. Besides mechanical microgrippers, vacuum microgrippers are especially widely used in handling larger microparts of hundreds of microns due to their simplicity. Other handling techniques have been researched and used in a limited set of applications.

A mechanical microgripper, usually having two jaws or fingers and operating based on friction force or form closure, is one of the most popular types of end-effectors in contact handling of microparts. The size of such grippers is usually in the range of several millimeters to centimeters [14, 25, 49-51]. Compliant mechanic structures are widely used in microgrippers. The jaws or fingers are usually made of metals (e.g. stainless steel [14, 22, 25], nickel [51]) or silicon materials [50, 26]. Some nanogrippers are also developed by applying nanotubes [52] or AFM cantilevers as the end-effector [32]. A mechanical handling microgripper can be actuated by various actuators, e.g. piezoelectric stacks [53], piezoelectric benders [14, 25, 51], shape memory alloy (SMA) [54, 55], thermal and electrostatic [43, 56], or various miniaturized linear motors. Passive microgrippers have also suitable applications, such as in [26]. To control the gripping force, force sensing is needed in microgrippers. However, due to the small dimension of the tips and jaws, force measurement is more challenging than in the conventional handling tools. For relatively large microgrippers, it is possible to apply miniaturized strain gauges [14, 25] AFM cantilever [57] or specially developed forces sensors [58]. For silicon based microgrippers, force sensor needs to be included in the fabrication process. Most microgrippers are designed for handling specific shaped objects and have a fixed initial opening. To handle objects of different sizes, tip exchange [59] or opening adjustment [25] are needed. Moreover, the alignment of the gripper tips will be influenced by the ambient environment such as temperature and humidity. Therefore, it is very important to have manual

adjustable tip alignment as proposed in [25] or active adjustable tip alignment as in the multi-DOF microgrippers [51, 60].

To achieve effective microhandling, good control systems and strategies are necessary. Control in microhandling exists at several levels. The first is local control of an actuator or a motion axis. Depending on the process, local feed-back control can be relative straightforward or rather complicated. Issues such as sensor drift due to actuator heating and ambient environmental change have to be treated. In the case a sensor is not available, a proper strategy is needed to control the actuator. For nonlinear actuators such as piezoelectric actuators, model-based control or current control need to be applied [61]. Control of the operational force is another challenging issue due to the small dimension of the end-effector and the required sensitivity. Force control is needed in many applications such as indentation test, or to avoid applying excessive force to the micro objects, e.g. MEMS parts and biological cells. In addition to measurement of gripping forces, dedicated end-effectors with integrated force sensors have been developed, e.g. [58, 62]. However, the sensitivity of those force sensors is usually at micro Newton level which limits their applications. Other techniques such as estimating operation force based on machine vision has been developed to tackle the problem [63]. The second level is global control of the micromanipulation system. In the case of telemanipulation, the operator can close the loop. Techniques such as multi-model control can effectively improve the performance [64]. When bilateral control is needed, the task becomes interesting and many studies have been carried out, e.g. [65 - 68]. However, due to the fact that the microforce measurement is difficult, bilateral control can only be applied in a limited set of applications. The third level is automatic control of the micromanipulation system. A typical method is a machine-vision based control algorithm with on-line and off-line programming [9, 69, 70], where visual servoing is often used. Due to the adhesion forces in the microworld, fully automatic manipulation is still a challenging task especially for 3D manipulation of parts having size in low microscale.

Despite the active research in contact microhandling, only a few systems are capable of dexterous handling, due to the difficulties and complexity in development of mini/micro mechatronics, e.g. two-fingered microhand [13], orthogripper [14], 4 DOF gripper [51]. On the other hand, most of reported microhandling systems are teleoperated. One of the reasons is that the integration of sensors into miniaturized systems is typically very challenging or, in some cases, impossible. Operator visual feedback via microscopes/monitor is commonly used in microhandling systems. In [13], the master-slave control system is used where the master is a two-fingered system with force/torque sensors. A control strategy composed of global motion and local motion controller is designed to control the master-slave teleoperation system. Automatic dexterous microhandling based on microgripper has been also reported. Due to the small amount of existing dexterous microhandling systems, automatic control systems and strategies are even less. In [16], the two fingers of the orthogripper are controlled individually through a force and a position sensor. Based on the sensor information and the model of the gripper, automatic dexterous manipulation (two axis rotation) has been achieved. A script language is used to control each operation with certain parameters. In [24], a force/position closed loop control strategy is developed for the 4 DOF gripper of [51], including a position control loop and a force limiter in the longitudinal plane.

Micro-optoelectronic components are nowadays manufactured with massively parallel processes, producing large batches in one run. The manufacturing processes are quite well developed, based on the techniques originally developed for microelectronics. However, automating the processes still remains a challenge. The main reason is that the handling systems based on miniaturized version of traditional systems are not adequate to handle the micro

components. Quality inspection, in particular, is sometimes still done by sampling the batches and performed manually. To automate the inspection process, micro components have to be handled and positioned properly. When using high magnification and high numerical aperture objectives, the limited depth of field of microscopes requires precise positioning and orientation of the micro components. Moreover, high spatial resolution is needed from the optical system in order to get precise information about the micro components and defects. However, this also effectively limits the depth of field of the objective. If the component is not wholly in the focal plane of the microscope, part of the component appears out of focus making it impossible to inspect all the details on the component surface. To overcome the low depth of focus of microscope images, one way is to scan the microscope at different distance to form a single, high depth of focus image. However, forming such an extended depth of focus image from a high resolution image stack is a time consuming operation. Instead of forming such an image, the best focused images of the image stack can be used to determine the pose of the component. Then a microhandling tool can position and pose the micro component accordingly. The quality of the target component can then be inspected as the component faces appear fully in focus and undistorted. Additionally, the micro components are usually manufactured in batch and placed in carriers. With the increasing demand for higher quality of products, the micro components should be inspected in not only one side, but several sides. Thus, a microhandling tool is necessary to pick the micro components for the inspection tasks. A natural way is to combine the two requirements and design a microhandling tool that can carry out both the pick-and-placement operations and the positioning tasks for quality inspection.

This paper presents automatic control of a novel 6-DOF microgripper for dexterous handling and inspection of optoelectronics components. In the next section the mechanical structure of the microgripper is briefly introduced. The overview of control system architecture is presented in section 3, followed by detailed explanation of actuator control in section 4, motion planning in section 5 and task planning in section 6. The experimental results are discussed in section 7. Section 8 concludes the paper.

2. 6-DOF microgripper

The 6-DOF microgripper is part of the microhandling system designed for handling and inspection of small ($10\mu\text{m}$ - $500\mu\text{m}$) micro components in 6 DOF in a workspace of approximately $180\times 180\times 30\mu\text{m}$. The microhandling system aligns components in 3D to the field-of-views of two microscopes for uniform focus. The gripper is implemented by a novel mechanical structure utilizes 2D piezoelectric bender actuators and piezoelectric stack actuators to achieve the 6 DOF. The gripper has a compact structure, modular design, as well as an advanced automation system. In order to meet the throughput requirements of applications in semiconductor industry application, the system should be capable of performing a single inspection cycle within a few seconds. The microgripper with its main components is presented in Fig. 1.

Figure 1. The 6-DOF microgripper and its main components: 1. electronic connection, 2. frame, 3. piezoelectric stacks, 4. strain gauges, 5. 2D piezoelectric benders, 6. detachable tips.

The main components of the microgripper include 4 piezoelectric actuators, 10 strain gauge sensors, an aluminum frame, an electric connection and a pair of end-effectors (tips). There are two mechanically separated arms which are mirrored about the y-z plane and otherwise identical. Each arm has 3 DOF at the tip of each arm. Both arms are bonded on the aluminum frame.

The gripper uses two different types of piezoelectric actuators, of which 2 are stacks manufactured by Piezomechanic and 2 are double benders manufactured by Noliac. The stacks have a maximum stroke of $30\mu\text{m}$. The double benders can bend along two nearly orthogonal axes, both having an estimated stroke of $180\mu\text{m}$ and an estimated blocking force of 0.18N . Each arm of the gripper is composed of a stack, a double bender, and a microfabricated SU-8 tip bonded together. Both double benders are glued on the stack with a 20° angle via adaptation pieces. When the gripper is installed horizontally, the tip has a 20° angle to the surface of the working platform.

The piezoelectric actuators are controlled in closed loop to compensate the non-linearities of the actuators. The feedback of the local controllers is provided by 10 strain gauges that are glued on the piezoelectric actuators (model Kyowa KFG-2N-120-C1-11N15C2), 1 for each stack, 4 for each double bender (in 2 pairs, one pair measures the displacement in x axis and the other pair for y axis). The size of the microhandling system (including the frame and the base) is $50 \times 50 \times 35\text{mm}$. Details of mechatronics of the microgripper are reported in [60].

To achieve automatic handling and inspection, the microgripper is integrated in an inspection system for optoelectronic components. The overview of the microhandling and inspection system is presented in Fig. 2 and Fig 3. In the system, the microhandling part consists of the 6 DOF microgripper and two commercial ultrasonic translation stages, referred as the z-axis positioning stage and the scanning stage in the following.

Figure 2. Overview of the microhandling and inspection system (design).

Figure 3. Picture of the microhandling and inspection system.

The purpose of the microgripper is to pick micro components from the GelPak™ vacuum releasing pack and position it (together with the ultrasonic motors) in 6 DOF so that the parts can be inspected by a machine vision system through the microscopes. The microgripper is installed on the ultrasonic motors to increase the workspace of the gripper beyond the range of the piezoelectric actuators. After inspection, the micro component is then placed back onto the GelPak™. Two microscopes are used for machine vision and inspection of the micro components. A coarse positioning system is also planned to move the GelPak(s) containing the micro components.

3. Control system architecture

The architecture of the control system for the microhandling and inspection system is presented in Fig. 4. To ensure the real-time performance of the control system and flexibility of the high-level control, a network based distributed control system is used, which includes three computers: a GUI PC, a real-time control PC, and a vision system PC.

Figure 4. Control system architecture.

The GUI PC is dedicated to the graphical user interface of the control system. The GUI and

controlling software run on separate computers mainly because running the graphical user interface, on Windows XP, degrades the real-time performance of the control loop. The real-time control PC performs the controlling of microhandling system. It runs a light-weight control loop at 1 kHz. The vision system PC has two main tasks. The primary task of the vision system PC is to analyze the surface properties of the component being inspected based on the images captured by the microscopes. The secondary task supports the primary task by providing feed-back data (the pose and the position of the component) to real-time PC. This is necessary since the depth of field of the microscope is relatively small, less than ten micrometers and therefore prior to inspection, the component must be aligned properly to the field of view of the microscope based on visual feedback. All three computers communicate via Ethernet using TCP/IP protocol.

To effectively carry out tasks of both actuator control and high-level automation, the software architecture of the real-time control PC consists of three hierarchical layers (see Fig. 5): actuator control layer, motion planning layer, and mission layer.

Figure 5. Hierarchy of the control system.

The **actuator control** layer is the lowest layer of the control system; it is responsible for driving and maintaining the tool at desired positions given by the set-points, coordinates in Cartesian space, from the high layers. This layer sends the output voltages and reads the feed-back data from the strain gauges via DA/AD boards. A mapping matrix is used to map the set points from Cartesian space to actuator space. Three SISO PI controllers are used for each arm.

The **motion planning** layer is the mid-layer between the mission layer and actuator control

layer. Its task is to generate the smooth trajectory for moving the tool between set points. This layer takes the control commands from mission layer in form of destination position of the tool or position and pose of the component. Motion planning level includes the mathematical model of the component manipulation.

The **mission control** layer manages the task execution at the highest level. A script interpreter is used for high-level control system. The mission layer commands the trajectory layer with higher level motion commands (e.g. “rotate component about z-axis by 10°”).

The three hierarchical layers are discussed in details in the following sections. The control system block diagram is shown in Fig. 6.

Figure 6. Control system block diagram.

4. Actuator Control

The actuator control layer is responsible for driving and maintaining the tool in the desired position. There are two important features in this layer: mapping of the strain gauges signals and the actuator control algorithm.

The microhandling system operates in Cartesian coordinate system. The orientation of coordinate system is as illustrated in Fig. 1. Therefore, the position of the tips also needs to be expressed in the Cartesian coordinate system. However, the computation of the position of the tips in the world coordinate system (discussed in Section 5) is based on the feedback data from the strain gauges. To estimate the position of the tips in the world coordinate system, mapping the strain gauge signals to the Cartesian space is required. Such mapping also solves two problems: kinematic coupling between different axes and sensor coupling between different axes. The positions of the tips are calculated as linear combination of three strain gauge measurement (one for each stack and two for each double bender) [60]:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = K \begin{bmatrix} sg_x \\ sg_y \\ sg_z \end{bmatrix} + \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} \quad (1)$$

where sg_x , sg_y and sg_z are measurement from the strain gauges of the double bender and the stack; x, y, z are the estimated position in Cartesian space; b_x , b_y and b_z are the bias terms. $K \in \mathbb{R}^{3 \times 3}$ is determined experimentally.

The calibration of mapping was performed using an external laser displacement sensor (MEL M5L/0.5 spot dimension 0.1 mm) that measures the displacement at the end of the tool. Besides the laser, an xyz translational stage is used to position the microgripper and a tilting stage is used to tilt the microgripper. The experimental apparatus is shown in Fig. 7.

Figure 7. Calibration apparatus.

To achieve reliable results, the end of the double bender is used as the reference point instead of the tip of the gripper. To solve all nine parameters, with sufficient accuracy, nine measurement from each arm is needed. The actuators are driven axis by axis while measuring the corresponding signals from all the strain gauges and the laser sensors. Since only one laser with adequate accuracy was used, the measurements were repeated for each actuator three times so that the displacement can be measured from all three directions. The actuators are driven using the maximum excitation voltage in sinusoidal wave at a frequency of 0.1 Hz. The K matrix is calculated from the experimental data row by row using least squares method.

The resolution of piezoelectric actuators is in the atomic range. However, piezoelectric actuators are quite non-linear (large hysteresis and creep) and therefore they are usually driven using closed loop control to achieve good accuracy. In practice the accuracy of the piezoelectric actuators is limited by the measurement noise of the control system and calibration of the sensors.

The control algorithm that is used in actuator control is a PI control algorithm with anti-windup. The block diagram of the actuator control system is presented in Fig. 8. The system consists of six PI controllers, three controllers per arm, one for each actuator (stacks) or actuator axis (2D benders).

Figure 8. Block diagram of the actuator control system.

The feedback data of the servo control loop is provided by the strain gauges glued on the piezoelectric actuators. The set points from the motion planning layer in Cartesian coordinate system are converted to set points in strain gauge space using the inverse of the mapping matrices. This provides decoupled reference point for each actuator.

5. Motion planning

The motion planning layer takes care of trajectories of the microgripper and the stages at different working states: free-move state and manipulation state. The free-move state is used for motion planning in telemanipulation and in automatic handling when no component is gripped. The manipulation state is used for motion planning when a component is gripped by the microgripper.

5.1. Free-move state

When a component is not gripped by the microgripper, or in telemanipulation, both tips can be controlled freely within the limitation of their corresponding workspaces. Both fingers have 3 DOF thus the gripper has altogether 6 DOF. After received a set-point from higher layer, the motion planning algorithm firstly validate the set-point value with the known workspace of the gripper, then interpolate the trajectories of all actuators based on specific velocity of each actuator. When the stages are used, we have altogether 8 DOF. In automatic handling, the motion planning layer takes care of distributing the workload between the stages and the gripper: when the set-point is within the workspace of the microgripper, the set-point is sent to the microgripper; otherwise, the set-point is sent to the corresponding stage if exists. In telemanipulation, both stages are controlled directly by the operator.

5.2. Manipulation state

When a component is gripped, the microgripper has 5 DOF for the object manipulation and 1 for the object gripping. Since the gripping must be maintained, the object can be translated in all three axes and rotated about two axes. Rotating the object about y-axis is performed by lifting one arm and lowering the other. Similarly, the rotation about z-axis is performed by the moving one arm backwards and the other forwards. With the help of an external object, the rotation about x-axis can also be achieved. The manipulation strategies and DOFs are illustrated in Fig. 9.

Figure 9. Manipulation strategies and DOFs.

In order to automatically manipulate an object, a mathematical model of the manipulation is needed. To avoid the complex vector analysis, the object manipulation algorithm is based on 3D homogeneous matrices. Relevant coordinate systems in the object manipulation algorithm are:

- World Coordinate System (WCS), which is the main coordinate system of the inspection system, as shown in Fig. 1 and Fig. 10.
- Object Coordinate System (OCS), which is located in the center of the object to be inspected

The object manipulation with relevant coordinate systems is illustrated in Fig. 10. The contact between the tips and the object is modeled as point contacts on the surfaces of the object. The initial condition assumes that the position of the object in the WCS, position of the tips in WCS and the size of the object are known. With such initial condition, we can easily calculate the position of the contact point between the tips and the objects in WCS.

Figure 10. Object manipulation.

The first job is to calculate the contact points between tips and the object in the OCS based on the values in the WCS. The contact points are obtained from the initial position of the tool and the initial position of the object in WCS. The object manipulation algorithm assumes that

the contact points remain constant in the object coordinate system after the object is grasped. To translate and rotate the object, we calculate the new transformation matrix $WCS \rightarrow OCS$, and then use the inverse of this new transformation matrix to calculate the new position of the tips in WCS. To simplify the presentation, the calculations are only made for one contact point.

Let the known initial contact points in WCS be ${}^W p_0, {}^W p_0 \in \mathfrak{R}^{3 \times 1}$, as shown in Fig. 10.

The original transformation matrix ($WCS \rightarrow OCS$) ${}^{WO}T_0$ is:

$${}^{WO}T_0 = \begin{bmatrix} R_0 & T_0 \\ 0 & 1 \end{bmatrix} \quad (2)$$

where $T_0 \in \mathfrak{R}^{3 \times 1}$ is the translational part of the matrix, $R_0 \in \mathfrak{R}^{3 \times 3}$ is the rotational part of the matrix.

The general orientation transformations in the calculations are done using roll-pitch-yaw transformation that is obtained from:

$$\begin{aligned} RPY(\phi, \theta, \psi) &= Rot(z, \phi)Rot(y, \theta)Rot(x, \psi) \\ &= \begin{bmatrix} C_\phi C_\theta & C_\phi S_\theta S_\psi - S_\phi C_\psi & C_\phi S_\theta C_\psi - S_\phi S_\psi \\ S_\phi C_\theta & S_\phi S_\theta S_\psi + C_\phi C_\psi & S_\phi S_\theta C_\psi - C_\phi S_\psi \\ -S_\theta & C_\theta S_\psi & C_\theta C_\psi \end{bmatrix} \end{aligned} \quad (3)$$

where C is the Cosine of given angle and S is the Sine of given angle.

When the object is gripped the initial contact point of the gripper in the OCS is calculated from:

$${}^O p = {}^{WO}T_0^{-1} \cdot {}^W p_0 \quad (4)$$

where ${}^W p_0 \in \mathfrak{R}^{3 \times 1}$ is the initial contact point in the WCS.

When the object is translated and rotated the new transformation matrix ($WCS \rightarrow OCS$) ${}^{WO}T_n \in \mathfrak{R}^{4 \times 4}$ is given by:

$${}^{WO}T_n = T \cdot {}^{WO}T_0 = \begin{bmatrix} R_m R_0 & R_m T_0 + T_m \\ 0 & 1 \end{bmatrix} \quad (5)$$

where $T \in \mathfrak{R}^{4 \times 4}$ is the desired relative transformation of the object, $R_m \in \mathfrak{R}^{3 \times 3}$ is the rotational part of T and $T_m \in \mathfrak{R}^{3 \times 1}$ is the translational part of T , similar to (2).

The new set points for the tool in WCS can then be calculated:

$${}^W p_n = {}^{WO}T_n \cdot {}^O p_0 \quad (6)$$

Based on the above manipulation model, we can calculate the desired tool position based on the desired translation and/or rotation of the objects and the initial condition of the micro components. Usually the desired translation and/or rotation is relatively large that cannot be reached in a single step. Therefore, linear interpolation is used to calculate the trajectories of the set-points for all actuators based on a specific speed of the actuators:

$${}^w p_i = {}^w p_0 + i \left(\frac{{}^w p_n - {}^w p_0}{k} \right) \quad i = 1 \dots k \quad (7)$$

where k is determined by a specific velocity of actuators v :

$$k = \max \left[\left({}^w p_n - {}^w p_0 \right) / v \right] \quad (8)$$

A simulation run of the object manipulation is presented in Fig. 11 using MATLABTM. The figure shows the trajectory that is generated for both arms when the object is translated and rotated simultaneously.

Figure 11. Matlab simulation of the object manipulation.

Similar to the case in the free-move state, the motion planning layer also takes care of workspace validation and distributing the workload between the stages and the gripper: when the set-point is within the workspace of the microgripper, the set-point is sent to the microgripper; otherwise, the set-point is sent to the corresponding stage if exist.

Another important issue that must be considered in the object manipulation algorithm is the gripping force. The force to hold and lift the object is provided by the stress at the gripper's arms, which is a result of the difference between the current position of the tool and its set point. In the control point of view this means that an error should always exist between the current position of the tool and its set point while gripping the object. In other words, the set point of the tool should actually lie inside the object, which is also illustrated in Fig. 11. In the current configuration, the set-points are 25 microns inside the chip for both tips. Due to the difficulty in force measurement at small scale, currently the forces generated by the displacement delta are not calibrated. Also, due to the object uncertainties, the position/pose estimation based on the algorithm has an estimation error, as discussed in Section 7.

6. Mission Control

The two main components in the mission control layer are machine vision and session control. The machine vision runs on a separate computer and communicates with the microhandling system via TCP/IP.

6.1. Machine Vision

The machine vision system consists of two Matrox Meteor2-MC grabbers, two greyscale cameras from Sony (XC-ST70CE and XC-HR300NC), two objectives from Mitutoyo (M Plan Apo 10× and 20×) and two coaxial led illuminators with controlled voltage levels. A computer is equipped with 3 Ghz Intel PentiumTM 4 processor with 1 Gb of memory using Windows XP professional.

The XC-HR300NC is installed on the 10× objective and the XC-ST70CE is installed on the 20× objective, using Infinity's InfiniTubes. The 20× objective is used for imaging the top side, and the 10× objective is used for imaging the front side of the component. The area of pixels used for XC-ST70CE is 736×575 and the spatial resolution is 0.585×0.567 $\mu\text{m}/\text{pixel}$. For the XC-HR300NC, the area of pixels used is 766×580 and the spatial resolution is 0.878×0.882 $\mu\text{m}/\text{pixel}$. XC-ST70CE has a 2/3" CCD sensor, while XC-HR300NC has a 1/2" CCD sensor.

The inspection system with the microscopes and coordinate system of the machine vision is presented in Fig. 2. The task of the machine vision system is to calculate the position and pose (x, y and z position, roll pitch yaw) of the microcomponent. To achieve this, imaging the components from the top view microscope is sufficient. The front view of the component is used mainly for quality inspection of that side, but it can also be used to check the rotation about y-axis calculated from the top view.

At first, the z-axis position of the component is calculated from a stack of images. The microgripper moves the component towards the objective of the top view microscope with constant-size steps. After each step, an image is grabbed. From this image, a gradient image is formed with Sobel operators and added to the image stack. A normal sized image stack consists of 10 to 30 frames with step size of 1 - 2 μm , depending on the required accuracy. The depth of field of the objective is only 1.6 μm , so only a few images are focused. A range map is then calculated from the stack. The range map is formed in such a way that every image pixel corresponds to the highest gradient value of the stack at that point, i.e. the best focus pixel. Dividing the range map to four regions, i.e. up-left, up-right, down-left and down-right areas as shown in Fig. 12, we can identify the image that is in best focus in that area by calculating histograms for those quarter images. The best focused image numbers correspond to the highest peaks of the histograms. The machine vision system then sends the identity number of the best focused image of each region to the microhandling system for both z-axis positioning and rotation about x-axis and y-axis.

Figure 12. Quarter images.

The x and y position and the rotation about z -axis are calculated from projected edges of the component. The edges are first obtained by taking adaptive threshold from the quarter images and then combined to a whole image again. This results as a binary image of the component with accurate edges, but it also includes inconvenient edges from the shapes on the component. The edge image is therefore filled with a special filling algorithm to remove the undesired edges. From this image, $I(x, y)$, the centroid can be calculated through the zeroth and first order spatial moments.

Thus, the (x, y) location of the centre point of the component is obtained. After this, the filled edge image is dilated. Then by subtracting the filled image from the dilated one, the outer boundaries of the component are obtained.

For dilation, a 3×3 rectangular structuring element having its origin at the centre is used. The process for obtaining the filled binary image of the component and the boundaries of the component is illustrated in Fig. 13.

Figure 13. The process of obtaining the edges of the component.

However, when the component is between the gripper tips, some of the coaxial light is blocked and the illumination of the component is not even. The left and right edges of the component are also easily blocked by the manipulator fingers, so the contours do not give accurate information about the component's pose anymore. Therefore, we only use the upper and lower edges of the component to calculate the rotation about z-axis as shown in Fig. 14. This is done by fitting lines through the edges. Mean square error is calculated for the lines to see how well they fit. A weighted average according to the mean square errors is then taken from the angles of the lines, and is used as the final rotation angle around the z axis.

Figure 14. Rotation about z-axis calculated according to upper and lower boundaries of the component from the top view.

The rotation about y-axis can also be checked from the front view. For this, the same algorithm as for obtaining the rotation about z-axis can be used, except that only one image is taken for the adaptive threshold. In this case, the fingers of the manipulator are not seen due to

the small depth of field ($3.4\mu\text{m}$) of the front microscope.

6.2. *Session control*

Session control manages the task execution at highest level. The system operation can be controlled with a simple scripting language. The script commands include for example: move the tool to initial position, grasp component etc.

The session control is also the level that connects to machine vision computer for vision based control. The visual feedback data is required in the subtask that controls the positioning of the component to the focus of the inspection microscopes. As described in the previous section, the system gradually moves the component upwards, while the machine vision captures a stack of images that are used to calculate the best focused quarter of the component. The machine vision computer then returns the identity numbers of the best focused quarters to the control system.

Using the identity numbers, step size and the size of the component, the control system determines the x and y rotations of the component by assigning vectors to the best focused quarter images and the distances between them. Vectors from up-left to down-right corner and up-right to down-left corner of the component are formed. The two vectors form a plane, and the x and y rotations of the component are then calculated in the image plane accordingly. The rotation about the z-axis and position in the x and y axis are give directly by machine vision. After the rotations about the x, y and z-axis and the position in the x, y axis and the best focus in the z-axis are known, the control system performs required manipulations to position the component to the focal point.

7. Experiments and results

To demonstrate the performance of the system, firstly automatic manipulation of micro component is tested, then a pick, alignment, inspection and placement cycle of a micro component was performed fully automatically. In both tests, $300\times300\times100\mu\text{m}$ commercial optoelectronics components were used. The system setup is shown in Fig. 15.

Figure 15. System setup.

7.1. Automatic manipulation test

The purpose of the manipulation test is to measure the accuracy of the component manipulation. A sequence of manipulations is performed and the pose and position of the component are measured using the inspection microscopes. For each position query (front of top) the machine vision calculates the centre point of the component and its rotation about the axis that is orthogonal to the image plane. The centre point coordinates obtained from machine vision are in pixels. Those values are then converted to micrometers based on the spatial resolution of the front microscope of $0.878 \times 0.882 \mu\text{m}/\text{pixel}$ and the top microscope of $0.585 \times 0.567 \mu\text{m}/\text{pixel}$.

Table 1. Manipulation accuracy

Set-point	Translate x 50 μm	Translate z 20 μm	Rotate y 12°	Rotate z 3.5°
MV Result	52.77 μm	21.79 μm	12.39°	3.61°
Standard deviation	2.96 μm	0.48 μm	0.98°	0.31°

The results are shown in the Table 1. The first row shows the manipulation set-points. The mean of machine vision estimation of the results is shown in second row and corresponding standard deviation in third row. The results show that the repeatability of the object manipulation is about $\pm 3 \mu\text{m}$ for a $50 \mu\text{m}$ displacement in the x-axis and $\pm 0.5 \mu\text{m}$ for a $20 \mu\text{m}$ displacement in the z-axis; in the case of rotation the value is about $\pm 1^\circ$ for a 12° rotation about the y-axis and $\pm 0.3^\circ$ for a 3.5° rotation about the z-axis. Considering possible sliding between the tips and the micro component and deformation of the tips and the gripper arms, the results of sensor-based control are rather good and sufficient for correcting the pose and displacement

error of the micro component in inspection task without using visual servoing.

7.2. Automatic inspection test

For the inspection of the commercial optoelectronic components, the basic cycle is: 1) the gripper moves to its home position while the micro component is moved to the predefined position; 2) the microgripper picks the component from the GelPakTM; 3) the gripper moves the component vertically in steps and after each step the top camera grabs an image of the component; 4) the location of the best focused image and the orientation of the component is calculated from the stack of images; 5) microgripper corrects the angular errors and moves the component to the position of the best focus, the top of the micro component is inspected; 6) the front of the micro component is inspected. Then the component is placed back to the GelPakTM. The preliminary experimental operations are illustrated in Fig. 16.

Figure 16. The inspection cycle: 1. initial position; 2. gripping the component; 3. lifting the component; 4. finding the best focus; 5. aligning the component and quality inspection from the top; 6. quality inspection from the front.

Fig. 17 shows the reference signal, position and angle estimation of the micro components, and corresponding errors from the sensor measurements. Only the reference signal of the z-axis stage is shown because it is not possible to measure the position of the stage in real-time with its device driver. The accuracy of the z-axis stage is below $0.5\mu\text{m}$ based on our tests so it should not affect the correctness of the results. The operation is divided into 12 segments and the functions are illustrated in the caption of the figure. The picking operation, including motion of both the z-axis stage and the microgripper, takes about 1.1s; and similar length of time is spent for the placing operation. The position error in the x, y and z-axis and angular error about the y and z axis at 0.7s are caused by the acceleration of the z-axis stage. In the D segment, the microgripper reduces the gripping force a bit by moving the set-points of the tips closer to the side walls of the micro component to increase the workspace of the microgripper for object manipulation. Even though no displacement can be observed, the action can be seen from the measurement of the strain gauges on the y-axis, as shown on the second last row of the figure, where the estimated displacement are changed. The reason that the gripping force should be relatively high at the B segment is to overcome the adhesion between the micro component and the GelPak surface, even though vacuum has been applied automatically to the GelPak before

the B segment starts. The E segment lasts about 1.4s, which is dedicated to determine the position and pose of the micro component by moving the micro component in 10 steps through the focal plane of the top microscope. It can be noticed that after the first 5 steps the microgripper reaches its workspace limitation and the motion planning algorithm redistributes the work in the following step such that the z-axis stage moves a step and the gripper returns to its home position to perform the next 5 steps. The segment F is used for analyzing the image stack obtained in the segment E. Therefore, the position and pose estimation costs 2.4s in total, which can still be reduced by improving the performance of the algorithms. After the estimation, the microgripper corrects the errors in the segment G, which takes less than 0.1s. The following 2.5s are used by the machine vision algorithm to take inspection images and analyze the quality of the component. After that, the microgripper returns to its home position and the system places back the component to the GelPak.

Figure 17. Position and angle of the component during an automatic handling and inspection cycle: A) The z-axis stage lows the gripper to the GelPak surface (0 - 0.42s); B) The gripper picks the microcomponent (0.42 - 0.67s); C) The z-axis stage moves the gripper with the component vertically up (0.67 - 1.07s); D) The gripper reduces the gripping force on the micro component (1.07 - 1.35s); E) The gripper scans vertically and the camera grabs images (1.35 - 2.75s); F) The vision system analyzes the images (2.75 - 3.75 s); G) The gripper adjusts the position and the angle of the components to achieve the best focus for grabbing the inspection picture (3.75 - 3.80s); H) The machine vision inspect the quality of the micro component (3.80 - 6.32s); I) The gripper moves the component to the initial position (6.32 - 6.38s); J) The z-axis stage moves the gripper with the component back to the GelPak (6.34 - 6.82s); K) The gripper releases the component (6.82 - 6.95s); L) the z-axis stage moves the gripper to the home position (6.95 - 7.35s).

The experimental results demonstrate that the system is able to automatically pick the component and position/orientate it for focusing under the inspection microscopes and place it back. The whole procedure in the figure takes about 7.3s, while the mean of 10 experiments is 7.1 ± 0.3 s. In those 7 plus seconds, the handling operation costs about 2.4 seconds while the rest 5 seconds are used for vision related tasks.

In the experiment present in the paper, the filling algorithm developed and used in the test phase took a great deal of time and was used only to get clear edges of the target components under uneven illumination. In the follow-up development, we were able to get more contrast between the component and the background, thus making it possible to use a much faster method where the target object was thresholded from the image with the help of the histogram by taking only the amount of brightest image pixels corresponding to the size of the object. The outer perimeter, the contour of the connected pixel region, was then stored in a list and the line moments along the contour [71] and line fitting were used to get the right orientation of the components. Using this method, calculation of the pose from both the top and front view takes only 130 ms.

Moreover, the inspection software was delayed for visualisation purposes. Without the visualisation, the quality inspection of the micro component (both sides) takes only 0.9 seconds. For the automatic inspection, the visualisation should be disabled and the results should be examined from a database instead. Therefore, the cycle time for whole inspection process can reach less than 6 seconds without the visualization.

In the tests, the x and y correction does not occur because the original position of the micro component is at a predefined position, which is also the required initial condition for the system. In the case an error occurs, the system is also able to correct the translational error, which is easier to correct than the z-axis error and the angular errors presented in the test. In some situation, the component may occasionally slides between the tips of the gripper during the lift-off from the GelPak about the y-axis. This can be corrected by an additional step using external object such as a smooth substrate as shown in Fig. 9. By combining optimal gripping point (usual at the centre of a micro component) and automatic vacuum release, such situation rarely occur in our tests.

One common topic in microhandling is the adhesion forces. However, adhesion force is not a problem in this particular application because all the microhandling operations are taken place in the "controlled" condition, i.e. the micro component is either firmly gripped by the microgripper or stuck on the surface of the GelPak. Even though the application presented in this paper is a bit special, it is very realistic for real-world applications. In the future, if the microgripper will be applied in other applications when such "controlled" condition does not exist, we should develop a different kind of configuration using e.g. potential trap, which covers a wide variety of self-assembly processes and geometrical configurations.

8. Conclusions

This paper presents a prototype system for the challenging 6 DOF automatic dexterous handling of $300 \times 300 \times 100 \mu\text{m}$ sized micro components using a novel 6-DOF microgripper. A network based flexible distributed control system has been developed with well designed hierarchical levels. Combined with the machine vision based positioning and quality check algorithm, the system achieves a high level of automation. The experimental results demonstrate that the system is able to perform fully automatic pick-and-place and dexterous handling operations for the micro components. The system has been applied for inspection of

commercial micro-optoelectronic components and reached a cycle time of $7.1 \pm 0.3s$ (visualization on). Using improved algorithm and turn off the visualization, a cycle time of 6 seconds can be reached.

Compared with the previous 6DOF micromanipulators, e.g. [13], the presented system is more compact and better engineered with features such as exchangeable tips. Moreover, most of the other dexterous microhandling systems are teleoperated or only automated at task level. The presented microhandling system is a fully automated system that can carry out the whole inspection task including dexterous microhandling sequences.

The future work will focus on refinement of the vision algorithms, development of model based force estimator for better system reliability, and more advanced high-level intelligence for automatic fault analysis and recovery.

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