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Macro-Micro Manipulation with Visual Tracking and its Application to Wheel Assembly

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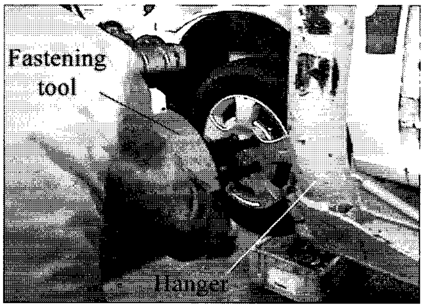
Abstract: This paper proposes a wheel-assembly automation system, which assembles a wheel into a hub of a vehicle hung to a moving hanger in a car manufacturing line. A macro-micro manipulator control strategy is introduced to increase the system bandwidth and tracking accuracy to ensure insertion tolerance. A camera is equipped at the newly designed wheel gripper, which is attached at the center of the end-effector of the macro-micro manipulator and is used to measure position error of the hub of the vehicle in real time. The redundancy problem in the macro-micro manipulator is solved without complicated calculation by assigning proper functions to each part so that the macro part tracks the velocity error while the micro part regulates the fine position error. Experimental results indicate that tracking error satisfies the insertion tolerance of assembly (± 1mm), and thus it is verified that the proposed system can be applied to the wheel assembly task on a moving hanger in the manufacturing line.

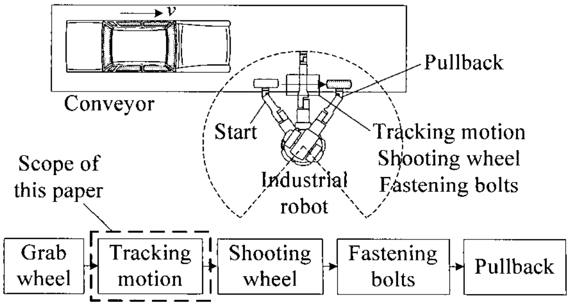
Keywords: Conveyor tracking, macro-micro manipulator, redundancy, visual tracking, wheel assembly.

1. INTRODUCTION

In a vehicle assembly line, wheel assembly is a labor-intensive process that requires automation. To automate the wheel assembly process, similar to other automation issues, it is very important to minimize the change of existing line set-up due to low cost requirement. In this circumstance, introducing an industrial robot is regarded as the best way to meet this requirement because the robot can replace laborers' capabilities. Therefore, in this work, we attempt to build a robotic wheel assembly automation system that is able to perform the assembly task while tracking the conveyor (or hanger) passing through the wheel assembly cell in the car manufacturing line. Current wheel assembly process manually performed by a laborer and its overall configuration in the assembly cell are described in Fig. 1(a) and (b), respectively. In an actual assembly line it takes almost 10 sec for wheel assembly (i.e., from tracking to pullback in Fig. 1(b)) by a laborer. Since the tasks of wheel shooting, bolt fastening, and pullback are conducted within very short time spans, most of the time is reserved for tracking a moving car in a conveyor line.



(a) Wheel assembly on a hanger by a human worker.



(b) Procedure of a robotic wheel assembly on a moving conveyor.

Fig. 1. Wheel assembly on the car production line.

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Many researches have been conducted on conveyor tracking systems with an industrial robot [1-4]. The conveyor motion usually possesses fluctuations in speed mainly due to its mechanical backlash in gears or chains. Most previous work could not adapt the fluctuation of velocity of the conveyor due to the massive structure of a manipulator. Kinematically redundant manipulators have been considered to overcome these limitations, but the redundant systems inherently have some complexities in controlling torques or velocities of joints.

In using redundant manipulators, redundancy resolution (i.e., deal with the redundancy) is usually conducted by optimization based approaches (e.g., null-space projection scheme [5-10]) and function-based approaches (i.e., application-specific approaches [11-14]). For optimization based approaches, most algorithms have dealt with a single physical property such as position, velocity and acceleration, which may cause several known problems such as singularities and instabilities (e.g., divergence of the command inputs) [10].

For the function based approaches, since these are application-specific (or practical) approaches, they can provide an intuitive control of a redundant system and easy implementation without any complicated computation. Furthermore, fast computation of control input of a manipulator provided by a function based scheme enables a real time application. The global and local deviations were measured by appropriate sensors in order to drive a macro-micro robot [11]. A base moving system was proposed to compensate for conveyor motion for the pre-planned task [13]. The moving base tracks only the conveyor motion, while the manipulator follows a predefined trajectory. However the manipulator on the moving base for conveyor tracking is usually massive, so it cannot cope with the fluctuation of velocity at high frequencies.

This paper proposes a macro-micro system using a real-time visual feedback for a robotic wheel assembly. A 6-dof industrial robot is used for the macro part, while a linear motor is equipped at the end-effector as a micro part to precisely track the conveyor motion, which has 1-dof in the task space. Many researches on a macro/micro manipulator have been conducted on a tracking task with a preplanned path [5,13,15]. In this study, however, our goal is to establish an on-line object tracking system to assemble a car hub into a moving car body. A camera attached at the micro part like an eye-in-hand system [16] measures tracking errors. A function based approach is applied to redundancy resolution to conduct a specific task (i.e., wheel assembly), since robustness and safety are required to apply a robot system to an actual environment. It is noted that singularities and instabilities arising from optimization based approaches can be avoidable with intuitive control of function based approaches. Usually the macro part (i.e., industrial robot) is massive and has a large working volume, thus it would be convenient for the macro part to track a large motion [5,17]. Therefore, to resolve redundancy in the proposed system, the macro part tracks the velocity error, while the micro part compensates the position error. PID based gains are implemented to control the macro and micro parts, respectively. Experimental results show that tracking error satisfies the tolerance of the wheel assembly.

This paper is organized as follows: In Section 2, the kinematics of the tracking system and its control schemes are presented; Section 3 deals with the design of the wheel gripper and its visual tracking method; in Section 4, experimental setup and results are discussed; finally, concluding remarks are drawn in Section 5.

2. MODELING AND CONTROL OF MACRO-MICRO MANIPULATOR

Since a car in an assembly line moves along with predefined paths due to the conveyor motion, the manipulator has several constraints concerned with the conveyor motion. Taking these constraints into account, a simplified kinematic model of the macro-micro manipulator is investigated. The redundancy of the macro-micro manipulator is resolved by the function-based scheme according to the simplified kinematic model.

2.1. Kinematic modeling

Fig. 2 illustrates a configuration of the macro-micro manipulator system. The macro part has 6-dof ($M = 6$) while the micro part has 1-dof ($m = 1$). Since the dimension of the task space is $n = 6$, the redundant dof

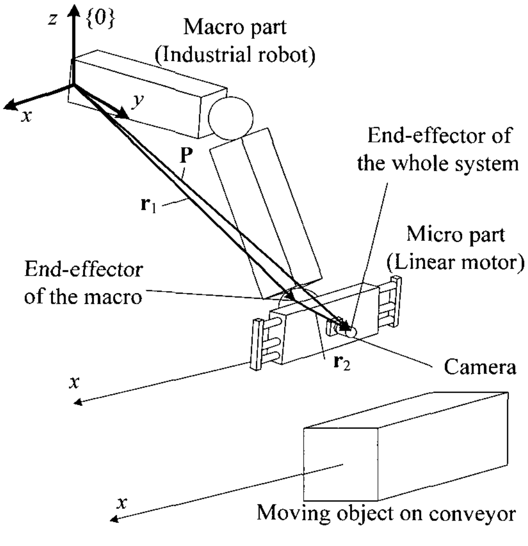


Fig. 2. Macro-micro manipulator system.

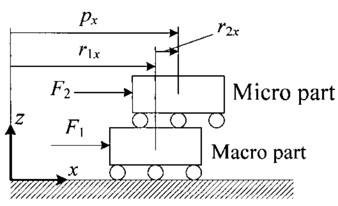


Fig. 3. Task space model of macro-micro manipulator.

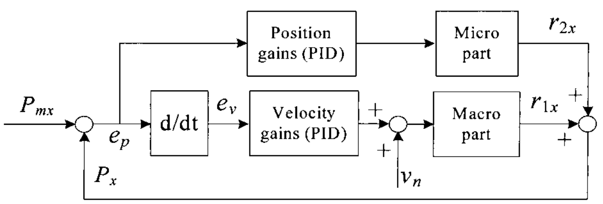


Fig. 4. Control block diagram.

(r) becomes 1 (= M + m - n). In Fig. 2, $\mathbf{P} \in R^n$ is a position vector of the end-effector of the whole system with respect to robot base frame {0}, where R^n represents an n-dimensional Euclidean space. Vector $\mathbf{r}_1 \in R^n$ is a position vector of the end-point of the macro part in the frame {0}, while $\mathbf{r}_2 \in R^n$ is a position vector of the micro part measured from the end-point of $\mathbf{r}_1$. Let $\mathbf{q}_M \in R^M$ and $\mathbf{q}_m \in R^m$ be the joint displacement vectors of the macro and micro parts, respectively. The whole joint displacement vector is represented by

$$\mathbf{q} = \{\mathbf{q}_M^T \quad \mathbf{q}_m^T\}^T \in R^{M+m}. \tag{1}$$

The velocity vector of the end-effector of the whole system $\mathbf{v} \in R^n$ is described by

$$\mathbf{v} = \mathbf{J}\dot{\mathbf{q}} = [\mathbf{J}_M \ \mathbf{J}_m]\dot{\mathbf{q}}, \tag{2}$$

where $\dot{\mathbf{q}}$ is a joint velocity vector, $\mathbf{J} \in R^{n\times(M+m)}$ is the Jacobian matrix of the whole system, and $\mathbf{J}_M \in R^{6\times6}$ and $\mathbf{J}_m \in R^{6\times1}$ are the Jacobian matrices of the macro and micro manipulators, respectively.

A conveyor (or a hanger) moves only along a predefined direction, so the desired motion of the object on the conveyor has 1-dof. Since alignment control of the micro part to the movement of the conveyer is conducted, the macro-micro manipulator system has five constraints in task space. Also assuming that the micro part is aligned parallel to a conveyor, the constraint can be applied only to the macro part. That is, the dof of the macro part is reduced to 1 by the constrained motion. Therefore, this macro-micro manipulator in Fig. 2 can be modeled as a simple double prismatic joint mechanism as shown in Fig. 3.

Assuming that only motion along the x-axis is available, a set of independent variables of the whole system in a task space can be written as

$$\mathbf{x} = \{r_{1x}, r_{2x}\}^T \quad \in R^{6+1-5}, \tag{3}$$

where r_{1x} (or r_{2x}) is the displacement of the end-effector of the macro part (or the micro part) in x-direction. Let $p_x \in R$ (i.e., x component of $\mathbf{P}$) be resultant motion of the macro-micro system. The p_x can be computed as

$$p_x = r_{1x} + r_{2x} \tag{4}$$

and v_x, which is a velocity of p_x, is

$$v_x = \dot{r}_{1x} + \dot{r}_{2x}. \tag{5}$$

2.2. Control algorithm for redundancy resolution

In this research, the function based scheme (assigning different objectives to each part) is applied to the redundancy resolution of the macro-micro manipulator. The macro part tracks the velocity of the end-effector of the whole system v_x, while the micro part compensates for its position error in a fine scale, similar to those in [5,17]. The output state of the macro-micro manipulator can be defined as

$$\mathbf{Z}_o = \{v_x, p_x\}^T \quad \in R^2. \tag{6}$$

The redundancy-resolution can be formulated as

$$\dot{\mathbf{q}}_M = \mathbf{J}_M^{-1}[v_x \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T, \tag{7}$$

$$\mathbf{q}_m = [p_x], \tag{8}$$

where $\mathbf{J}_M^{-1}$ is the inverse matrix of the $\mathbf{J}_M$.

Let p_{mx} and v_{mx} be the position and velocity of the moving object in the x-direction, respectively. The output feedback error can be expressed as

$$\mathbf{e} = \mathbf{Z}_m - \mathbf{Z}_o = [e_v \quad e_p]^T, \tag{9}$$

where $\mathbf{Z}_m$ = $\{v_{mx}, p_{mx}\}^T$, $\mathbf{Z}_o$ = $\{v_x, p_x\}^T$, $e_v = v_{mx} - v_x$, and $e_p = p_{mx} - p_x$.

The overall control schemes with redundancy resolution are illustrated in Fig. 4. The positional error e_p is measured by the camera in the micro part (i.e., eye-in-hand system). The macro part compensates the velocity error e_v to zero. In this case, the nominal velocity, v_n, is a desired velocity of the conveyor to be operated. PID based gains are applied to position and velocity controls, respectively, as shown in Fig. 4.

3. WHEEL GRIPPER AND VISUAL TRACKING ALGORITHM

In this section, the mechanical structure of the wheel gripper is presented and its visual tracking is discussed. Since both positional and rotational deviations between the car hub and the wheel gripper occur in an actual assembly line, they are required to be compensated with the visual information in real time.

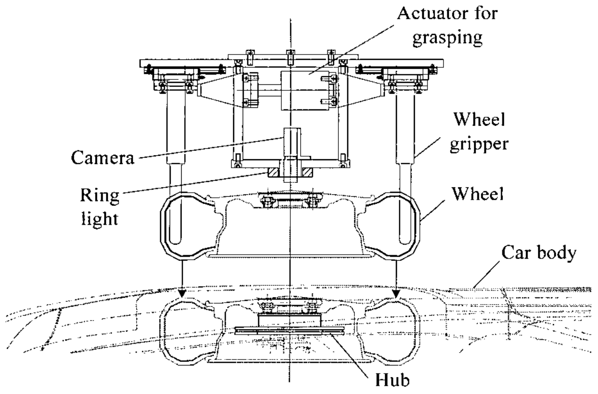


Fig. 5. The wheel gripper assembly drawing.

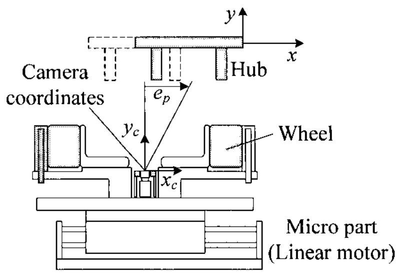
3.1. Wheel gripper design

The wheel gripper is depicted in Fig. 5. A camera is embedded into the center of the wheel gripper as shown in Fig. 5 and looks through the hub via a hole existing in the center of the wheel. Since the camera can be closely placed to the car hub, fine resolution is provided, thereby enabling precise measurement of the position of the car hub. A ring light is also attached around the camera to provide an invariant light condition. A six degrees of freedom industrial robot is included in the automated wheel assembly system and a linear motion device (i.e., the micro part) is attached at the end-effector of the industrial robot (i.e., the macro part). Finally, the wheel gripper described in Fig. 5 is attached at the end-effector of the micro part.

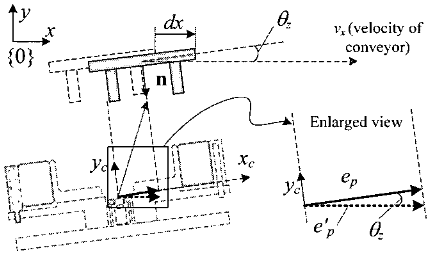
3.2. Visual tracking

A camera is equipped at the center of the wheel gripper as shown in Fig. 5. In an ideal situation, the car hub is well aligned in the direction of the motion of the conveyor as shown in Fig. 6(a). In this case, the position error e_p is directly computed from the position of the car hub in the image coordinates. Although the car hub is normally aligned before the assembly process, a small deviation of rotation of the car hub sometimes exists. Thus this alignment should be done to reliably assemble the wheel and car hub.

To estimate the deviation of the car hub, we adopt the computing method of an image characterisitc Jacobian matrix by using vanishing points [18]. The method can compute all rotaion angles of the hub (i.e., θ_x, θ_y, and θ_z) with a single camera system. Note that the car hub moves along the x axis (i.e., dx in Fig. 6(a)), even though the car hub has been rotated along the z axis (i.e., θ_z). The micro part should be aligned along with the rotation θ_z of the car hub. In this situation, the positional error of the car hub, e_p, with respect to the camera coordinates frame is illustrated in Fig. 6(b).



(a) Aligned car hub parallel to the conveyor motion.



(b) Car hub with small rotation.

Fig. 6. Schematic configuration of the car hub and wheel gripper.

Since the micro part has rotated around the z-axis, the normal vector of the hub (**n**) and the wheel gripper (i.e., y_c-axis) must be collinear to insert the wheel into the car hub. Hence, the position error e'_p with respect to frame {0} in Fig. 6(b) is expressed as follows:

$$e'_p = e_p / \cos(\theta_z). \tag{10}$$

To avoid collision of the wheel with the car hub as well as to make them collinear, the micro part is regulated with e_p and the macro part tracks the velocity error of e'_p. This control scheme enables assembly of the wheel, although the z-rotation of the car hub occurs. Note that rotational deviations in the x- and y-directions can produce positional errors like those in the z-direction. Similar control schemes are applied to compensate for them.

4. EXPERIMENTS AND DISCUSSION

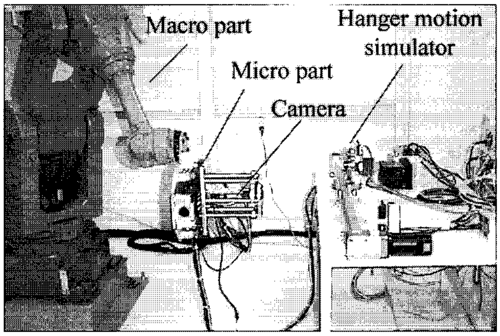
An experimental setup with the motion simulator of the car hub was constructed together with the macro-micro manipulator. It is found from various experiments that the position errors of the macro-micro manipulator satisfies the insertion tolerance, whereas the conventional manipulator (i.e., only the macro part) does not.

4.1. Experimental setup

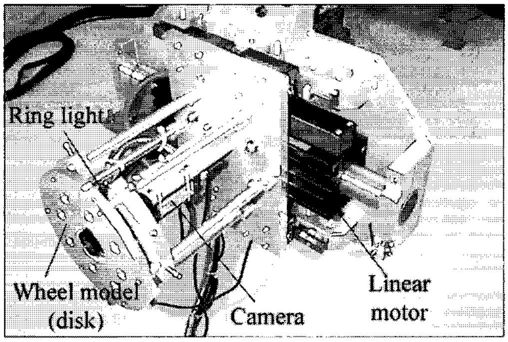
Since every assembly line must be stopped to apply the proposed wheel assembly system to the car manufacturing line, real implementation requires significant cost. Thus, we attempted to verify the proposed system with similar conditions to those of an actual assembly line at the Hyundai motor company.

Fig. 7(a) shows the macro-micro system and the conveyor simulator. The macro part is the Vorg industrial robot manufactured by Nachi Inc, while the micro part is developed with a linear guide driven by a linear motor as shown in Fig. 7(b). The camera is equipped at the center of the end-effector of the micro part. The conveyor motion simulator on the table consists of a linear actuator and a car hub mounted on the moving part of the linear guide as shown in Fig. 7(c). An encoder is also equipped at the driving shaft of a linear actuator to measure its position.

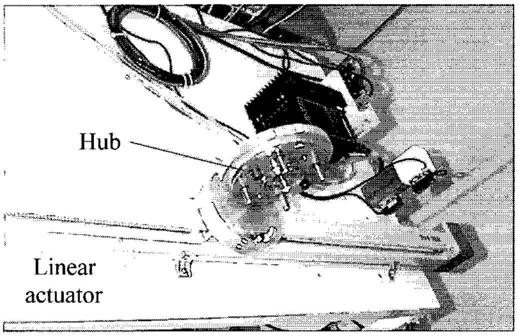
The experimental control system is illustrated in Fig. 8. The PMAC [19], a commercial DSP-based motion controller, is used for a main controller. The PMAC simultaneously controls three parts: the macro, micro, and the hanger motion simulator. The constrained motion of the macro part is achieved by using the conveyor tracking function provided by the robot manufacturer. In this experimental system, the PC only provides image processing data to the PMAC. Therefore, the real-time program for controlling all parts is established in the PMAC and its sampling period is up to 1ms. Since the actual hanger motion was measured in a real production line at the Hyundai motor company, the hanger motion simulator replayed the real measured data. The vision system provides the position error e_p of the center of the moving hub. The e_p is updated at 0.04sec intervals and transferred to the PMAC through DPRAM. A hub image captured by the vision system is shown in Fig. 9. To reduce pattern searching time, the search window is set as small as possible on the image as shown in Fig. 9.



(a) The whole experimental system.



(b) The micro part.



(c) Hanger motion simulator.

Fig. 7. Macro-micro system with hanger motion simulator.

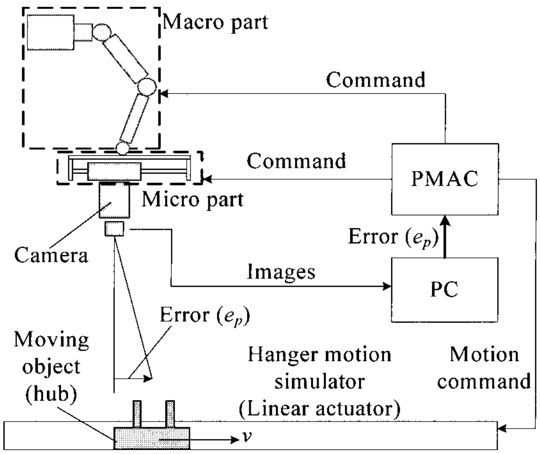


Fig. 8. Experimental control system.

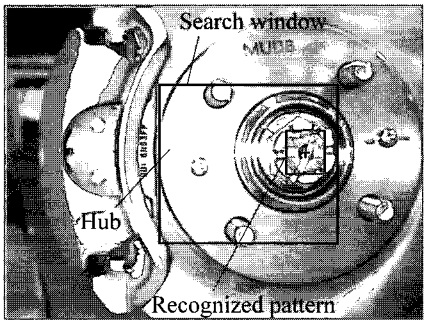


Fig. 9. Hub image captured with the camera.

4.2. Experimental results

Fig. 10 presents a velocity trajectory of the hanger motion simulator measured by the encoder. The nominal velocity of the real data is set to 0.1m/sec, and the maximum deviation of velocity is 70%. This means that the macro-micro system is required to track the highly fluctuated velocity trajectory to maintain the position error within the insertion tolerance of the wheel assembly.

The tracking experiment using only the macro part was conducted for evaluating tracking capability of

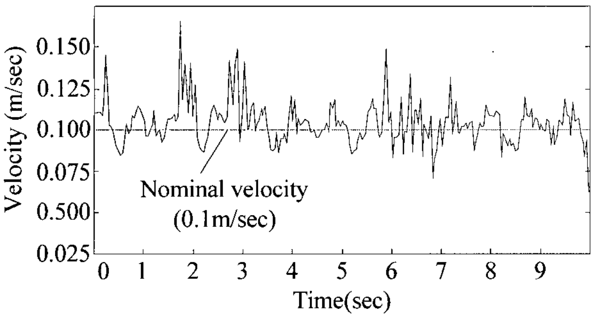
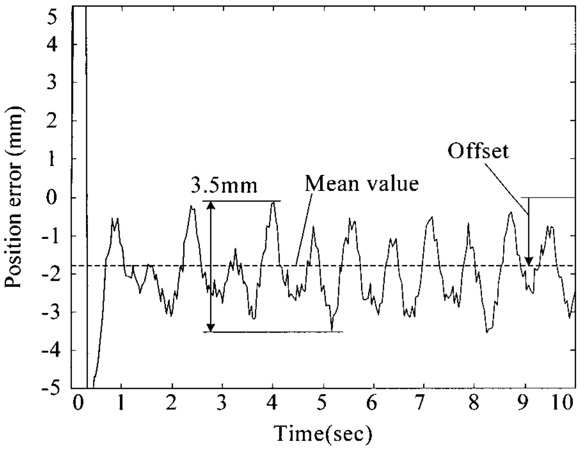
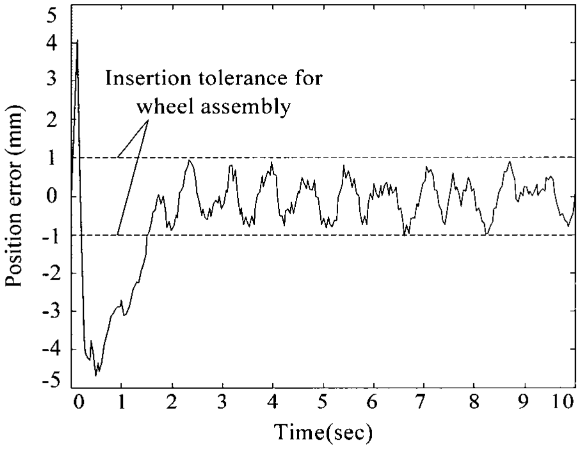


Fig. 10. Velocity of the hanger motion simulator.



(a) Tracking error of macro part.



(b) Tracking error of macro and micro parts.

Fig. 11. Tracking errors.

the macro part. Position errors on tracking are illustrated in Fig. 11(a). The max error is up to 3.5mm. The offset and oscillations come from the time delay mainly due to the low control rate, being 5Hz, of the conveyor tracking function. Therefore, tracking with only the macro part may be dangerous in assembly tasks, since the oscillation with large amplitude (3.5mm) causes great acceleration at the end point of the macro part, which is usually massive. Therefore, the result in Fig. 11(a) indicates that the macro part cannot provide fine tracking due to its low bandwidth, which leads to seriously dangerous situations.

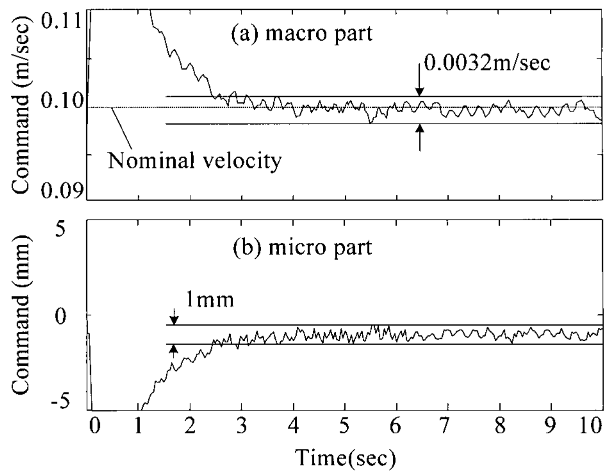


Fig. 12. Control inputs.

Fig. 11(b) shows the position error on a tracking experiment by the entire system (i.e., the macro-micro). Oscillations still exist and the settling time increases. However, their amplitude decreases to less than 1mm and their offset has a zero value. Thus, the insertion tolerance (±1mm) is satisfied with the macro-micro system. The control inputs to the macro part (Fig. 12(a)) and micro part (Fig. 12(b)) converge to the nominal velocity and position as shown in Fig. 12, respectively. In the steady state (after 3sec), the deviation of inputs to the macro part is bounded to 0.0032m/sec and that of the micro part is 1mm.

In the proposed system, the target position is updated every 0.04sec due to the update rate of the camera, which provides its image to an image grabbing board in the PC at 25Hz. As generally known, a camera with fast image transfer rates can increase the tracking performance.

5. CONCLUSIONS

This paper proposes a visual-tracking manipulator, which is practically applicable, consisting of an industrial robot as a macro device and a linear guide as a micro device for the robotic wheel assembly on a moving hanger with a car body. Since the motion of the macro part can be constrained to one dimension by the conveyor motion, the macro part is controlled by a single reference input. From this feature, the system model and its control method become simple. The redundancy in the macro-micro system is resolved based on a function based scheme in which the macro part tracks the velocity error, while the micro part tracks the fine position error measured by the camera attached at the wheel gripper. As a result, it is found that the tracking error of the macro-micro manipulator meets the insertion tolerance (±1mm) to enable the wheel assembly task successfully.

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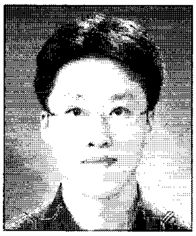

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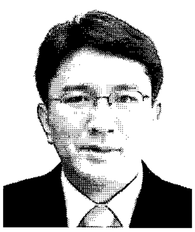

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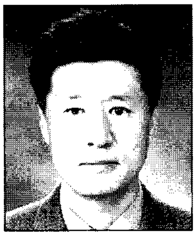

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