Abstract: In this paper new intelligent control strategies are presented allowing a cooperative work between a human operator and a microassembly platform working in a partially structured microworld. Human integration is essential in the microworld where autonomous control alone would not be successful. The allocation of the control among human and robot occurs dynamically according to the state of the task execution. In the following, different task-level control issues (shared, traded, cooperative and priority) are discussed and tested on a micro device assembly workcell.

1. INTRODUCTION

At present, operations to manipulate micromechanical parts (MEMS, MOEMS, micro-electronics), and biological cells (embryo, molecules,…) are accomplish manually with the help of micromanipulation systems. As the remote microworld is not well understood by the operator, augmented human sensing, scaled manipulation, dexterous haptic interfaces are concentrating most of the research efforts made on direct teleoperation [1-3]. In these cases, a human operator is inside the control loop and as all movements are executed directly by the manipulator, possible collisions due to fatigue, imprecision of scaled manipulation and lack of dexterity can destroy components in the microworld. Moreover, future mass production of 3-D MEMS will require fully automatic assembly of hybrid components with very limited human interaction in order to preserve potential economic benefits. A better solution for operating is to have the operator outside the control loop. The operator gives “high level” commands by depicting different tasks to reach a goal. In this case, we speak of supervised teleoperation. Different research projects are currently investigated [4,5,6] but the full automatic control approach in the microworld seems to be very challenging. The more autonomous the system is, the more structured the microworld should be, and more specific its tasks are. Small uncertainties in the microworld, such as, parameter variation between the world model and the real world, noisy visual sensing information or unpredictable dynamic effects (friction, adhesion) causes the microassembly system break down.

How to minimize microeffects on every level of planning and execution system? We do not try to eliminate the uncertainties in the environment nor increases the intelligence of the microrobotic system. The main idea is to compensate the uncertain and dynamic varying micro environments by the ability, decision-making, and intervention capacities of human behavior in order to intervene in supervising and controlling with different proficiency levels. The principle consists of sharing the control of the microrobotic workcell between the operator and the remote visual controller (RVC) according to the context of action, taking advantage of their unique strengths and helping each other in their areas of weaknesses in micromanipulation. Figure 1 illustrates such human-machine interaction during on-line execution of the programmed virtual tasks developed in this work.

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2. TELEOPERATED MICROASSEMBLY WORKCELL

Currently, the microrobotic assembly system consists of two concentrated motion micromanipulators (main and sub) equipped with a microtool holder, a coarse motion worktable (driving with piezoelectric actuators, the movable ranges: 30 × 30 × 30 mm), a multidegree of freedom fine positioning system (driving with piezoelectric actuators, the movable ranges: 100 × 100 × 100 µm). The orientation of the end-effectors can also be changed by two accurate ultrasonic motors. A reflecting light-type optical microscope (OM) is used as a top-view vision sensor. A high-definition camera on the OM is connected to the Matrox Co. Frame-grabber which enables real-time image viewing of the microworld on the teleoperator interface.

3. LIMITATIONS OF AUTOMATIC MICROASSEMBLY APPROACH

3.1. Task planning using Virtual Reality

The design issues of automatic microassembly include assembly planning (how the components can be put together?) and subtask planning (generation of instructions to the micromanipulators to carry out the assembly sequence). A typical pick-and-place task-based teleoperation approach has been modeled (positioning, handling and insertion) where the operator determines the elementary subtasks to be performed (Fig. 3), and the visually servoed controller realizes these operations with the aid of a virtual reality (VR) guiding-system interface. The description of the task plan is given in Table 1.
Fig. 4: Planning-based VR (a) of assembly tasks, through off-line programming. On-line assembly (b) of a gear hole in a desired axle by decomposition of the subtasks, i.e., transportation (pass pose1), alignment (pass pose2), and insertion (pass pose3).

The combination of vision servoing techniques and VR-based simulation system allows to plan the manipulation tasks and to insure the guided-movements of the micromanipulators preventing any collisions and also increasing safety and reliability of the distributed assembly workcell. In our system, a VR-teleoperator interface giving a 3-D map of the scene is provided to the user for automatic positioning sequences in an absolute frame. We build our VR application in C using WTK (World tool kit, sense8™) and then we added our C application in our master control application [7]. As illustration, Fig.4 shows planned and on-line execution of subtasks depicted in Table1: (a) coarse and fine transportation of the handled object is controlled by vision feedback (pass pose1), (b) then, alignment operation by controlling accurately the cooperative movements of both piezoelectric manipulators through 3-D viewing (pass pose2), and finally (c) automatic insertion operation of the microgear into a microaxle (pass pose3).

3.2. Error Recovery

From the previous experiments with the microassembly workcell, small uncertainties in the microworld, such as parameter variation between the virtual world model and the real world, noisy visual sensing or unpredictable dynamic microeffects (i.e. friction forces during insertion, sticking object to the gripper) lead to degraded operating modes on every level of planning. If an operation fails, the incident is reported to the supervision which analyses the fault either requests manual assistance. Classical full automatic task-plan approach was unreliable. Supervisory control strategy demands for sensor surveillance during the assembly plan, requests manual assistance during faulty micromanipulation, and requires support to solve the conflict between the internal model and the real microworld. Human integration into robot control is considered to compensate these limitations by the ability, the decision-making and the intervention capacities of human behavior.

4. HUMAN INTEGRATION IN ROBOT CONTROL

A method for integrating different levels of human-robot interactions into the task plan is given in the following which tolerates some degrees of uncertainty and gives some degree of freedom to the human. The integration of human in the "control loop" of the workcell needs to define, for each elementary subtask (SE) of the pick-and-place task, which is executed automatically, symmetrically semi-autonomous subtasks. These two levels of task execution, i.e., autonomous and semi-autonomous modes, are defined according to the degree of autonomy of the workcell facing to on-line execution problems. When the workcell is not able to accomplish the required task autonomously, it switches into the semi-automatic mode and gives then the operator the possibility to interact. Fig. 5 shows the scheme of integration of the human operator (OP) into the task plan. Contrarily to [10], we introduced a decision mode which activates the transition between the two levels represented by the bidirectional white arrows. The nature of the cooperative interaction between the operator and the assembly workcell changes according to the evolution of the task. To each SE corresponds a predetermined control allocation specified by the user during off-line programming. This control allocation is defined according to the capabilities of the robot and the human. A given degree of freedom is controlled by the partner of the human-robot team, who has the best sensing, actuating and cognitive capabilities to control it.
5. CONTROL ALLOCATION OF THE DECISION MODE

5.1. Basic Human-Robot Interactions

The question now is how do we combine basic behaviors to achieve a desirable supervisory control during the task plan? Let a human operator and the remote visual controller (RVC) defined by two vectors to cooperate for some task. Each process do the task by considering the contribution of the second one as shown in Fig.6a.

![Diagram](image)

Figure 6. Decision making between human and robot: (a) basic flow of information and (b) vector representation of the symmetric and asymmetric human-robot interaction.

The behavior function $P(x,y)$ expresses the human-robot interaction;

$$P(x, y) = e^{\frac{a x + b y + c y^2}{x^2 + y^2}} \quad \text{and} \quad x, y \in \mathbb{R},$$

(1)

where the variables $x$ and $y$ are the contribution of each partner. The constants are settled to $a=1.02889$, $b=0.3574$, and $c=0$. If we note $P(x,y)$, it implies that the second process $y$ acts by taking in consideration the contribution of the first process, $x$. On the contrary, the function can be reversed $P(y,x)$. From the definition of the behavior function $P(x,y)$, we can express the output behavior vector, $z$, resulting from the summation of the two input vectors (Fig.6a). The latter gives particular behavior outputs. In the following, several analogical gates illustrating the different human-robot interactions are defined. These gates are of two kinds: symmetric and asymmetric. The symmetric gates perform operations such as union (OR) and intersection (AND) while the asymmetric ones implement priority operations.

- Cooperative Interaction. We define the gate-OR as the result of a cooperation between two operators to perform some task. If $x$ is the contribution of the first operator and $y$ that of the second then the cooperation result is defined as:

$$z = x \oplus y = xP(y,x) + yP(x,y)$$

(2)

where $xP(y,x)$ is the contribution of the first operator by taking in consideration the contribution of the second one and $yP(x,y)$ means the reverse (see Fig.6b). Both operators contribute in relation to their magnitude. It is clear that this operation is symmetric. Now, we must impose properties to $P(y,x)$ of common sense:

(1): The cooperation of the same operator gives for both cases the same result, it means that $P(x,y) = 1/2$.

(2): The absence of cooperation of an operator does not act any more on the result. It means that $x \oplus 0 = x$ implying that for $x \neq 0$, $P(0,x) = 1$. In mathematical terms, zero is the neutral element of the $\oplus$ law.

(3): If one can define the opposite contribution $\neg x$ of $x$ then $x \oplus \neg x = 0$.

(4): The contribution of two operators is superior than the smallest contribution of both processes and less than the largest one $\min(x,y) \leq x \oplus y \leq \max(x,y)$. This relationship is true if we assume that $0 < P(x,y) + P(y,x) \leq 1$.

These properties can be summarized as follows:

- $z = x \oplus y = y \oplus x$
- $z = cx \oplus cy = c(y \oplus x)$
- $x \oplus -x = 0$
- $x \oplus x = x$
- $\min(x,y) \leq x \oplus y \leq \max(x,y)$

- Sustain Interaction. It is pointed out that the gate-AND is the negation of the gate-OR and by using a “probabilistic” reasoning we can deduce:

$$z = x \otimes y = x(1 - P(y,x)) + y(1 - P(x,y))$$

(3)

as negation of the OR function (2). The task is performed fastest when both processes simultaneously increase their performances. No task is accomplished if either process input is not activated. This operation is also symmetric as (2).

- $z = x \otimes y = y \otimes x$
- $z = cx \otimes cy = c(y \otimes x)$
- $x \otimes -x = 0$
- $x \otimes x = x$
- $\min(x,y) \leq x \otimes y \leq \max(x,y)$

When the two operators are closely related, the asymmetric gates implement priority relationships such as.

- Traded Interaction. The $x$-port is assigned an exceptional prevalence over the $y$-port. The latter is put-through directly.
to the output as long as the former is absent. However, once the input is at the prevalent port it strongly dominates the output. It is expressed by

$$z = x\Lambda y = xP(y, x) + yP(x, y).$$

(4)

where $n \in \mathbb{R}$ given more importance to $x$-port. It is clear that this operation is asymmetric but verifies all the others properties as in (2). It means that in the absence of the first operator the second does not act.

• $z = x\Lambda y \neq y\Lambda x$  • $x\Lambda 0 = x$ and $0 \Lambda y = y$
• $x\Lambda - y = -x\Lambda y$  • $\min(x, y) \leq x\Lambda y \leq \max(x, y)$

- **Shared Interaction.** As the $x$-input grows, the share of the $y$-input to the output is increased. The absence of $x$-input inhibits the output. In the absence of the $y$-input, the $x$-input is linearly passed to the output.

$$z = x!y = xP(y, x) + y\left(1 - P(x, y)\right).$$

(5)

Practically, it means that in the absence of the first operator the second does not act.

• $z = x!y = y!x$  • $x!0 = x$ and $0!y = 0$
• $z = cx!cy = c(y!x)$  • $x!-x = 0$ and $-x!x = 0$
• $x!x = x$  • $\min(x, y) \leq x!y \leq \max(x, y)$

### 6. Experimental Strategies of Human-Robot Interaction

Based on our approach, an experimental evaluation of the different strategies of human-robot interaction has been carried out for reliable and efficient 3-D microassembly.

#### 6.1. Shared Control

In shared control, the teleoperator and the RVC control different subtasks of the workcell simultaneously. A common example which has been tested is the position and force control during the pickup and the transportation of the microobject. The respective shared tasks SE5–6 are described in Fig.8a considering several factors. Firstly, collisions between objectives, micromanipulators and MEMS device occur due to the limited working distance of the microscope objective. Secondly, to guide automatically transportation operation through the entire assembly scene, it needs to implement an efficient multi-view tracking system which is not feasible. Considering those limitations, the human operator handles the position control of both telemanipulators using "moment-to-
mode (SE3 to SE4) or to the autonomous mode (SE5 to SE6) are initiated automatically. Experiments have shown that shared control was well adapted for subtasks where there was some, i.e., weakness of visual sensing through the entire assembly scene, restricted motion and dexterity due to obstacles or need for complex manipulation skills.

5.3. Traded Control

In traded control, the operator and the remote controller (RVC) take turns to control the workcell according to the situation of successful control. At the operation level, the subtasks are temporally assigned to the operator and the RVC according their fitness to the the subtask execution. We tested a microinsertion subtask as planed in Fig.10(a).

**Fig. 10:** (a) Function allocation according to the traded control task SE7-SE8 during semi-autonomous mode and (b) on-line execution.

The telemanipulator is following the predefined trajectory, which is taken temporally by the local remote controller under normal conditions. Since the assembly clearance is small (Fig 10(b)), the part contact the MEMS substrate after it moves into the hole. As friction forces are important, handling operation becomes potentially unstable. The assembly can be more tolerant of alignment errors due to compliance if the microgripper can be controlled actively. When the operator notices some disturbance forces during execution, he takes over the control and helps the telemanipulator with the aid of the joystick interface. The transitions to switch to the semi-autonomous mode from SE7 to SE8 are initiated manually when the operator applies the corresponding forces on the joystick. All SEs are guarded motion, so that if the applied forces cross a given transition threshold, the transition is initiated. After that, the operator will release the control to the remote controller. Figure 11 shows the measured position/force control applied by the operator to the one-armed manipulator to counteract friction forces. Critical situations should be avoided with the aid of human manipulation capabilities.

5. CONCLUSION

In this paper, we have addressed the problem of new strategies of control using multilevel man-robot interactions for automatic microassembly. The main idea is to find a compromise between workcell autonomy and human interaction. We present a method which integrates the human into the task plan according to the state of the execution. The combination of these capabilities occurs through the definition of behavior functions. Their experimental integration into the vision-based microrobotic workcell has shown their efficiency and reliability during 3-D microassembly tasks. Their main advantages are, i.e., the error occurs on-line, the operator interacts directly with the workcell, direct force/position human feedback and right mixture of robot autonomy and human interaction adapted to the state of the microassembly plan.

6. REFERENCES