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Simple coarse sensing to achieve high precision From attractive region in environment to constrained region in environment

Hong Qiao\textsuperscript{a,b,c}, Chao Ma\textsuperscript{d}, Rui Li\textsuperscript{a}, Xiaqing Li\textsuperscript{d}, Ziyu Chen\textsuperscript{d}, Wei Wu\textsuperscript{a} and Lijin Xu\textsuperscript{e}

\textsuperscript{a}The State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Science, Beijing, People's Republic of China; \textsuperscript{b}Chinese Academy of Sciences Center for Excellence in Brain Science and Intelligence Technology, Shanghai, People's Republic of China; \textsuperscript{c}University of Chinese Academy of Sciences, Beijing, People's Republic of China; \textsuperscript{d}School of Automation and Electrical Engineering, University of Science and Technology Beijing, Beijing, People's Republic of China; \textsuperscript{e}EFORT Intelligent Equipment Co., Ltd., Wuhu, People's Republic of China

\section*{ABSTRACT}
As a fundamental yet urgent issue, achieving high-precision robotic manipulation is becoming an active research area. Unfortunately, it is practically impossible to obtain an unlimited increase in sensor accuracy. In contrast, sensor-less manipulation approaches have attracted considerable attention. In particular, the concept of attractive region in environment has achieved encouraging results. Moreover, note that certain information cannot be captured directly from the sensors. With the above observations and inspired by the behaviour mechanism of human beings when accomplishing complex operations, this article proposed a novel bio-inspired co-sensing framework, which aims to solve the high-precision sensing problem by simple coarse sensors. One of the distinguishing features of the established framework is the constrained region in environment, the key idea of which is the integration of the relaxed constraint and the coarse sensor information. An illustrative example is provided to demonstrate the effectiveness and benefits of our theoretical findings.

\section*{1. Review of robotic manipulation}
As an important part of future automation technologies, robots are customized to enable high-precision manipulation in more and more tasks, especially for advanced manufacturing areas (Qiao, Li, & Yin, 2015; Zollo, Roccella, Guglielmelli, Carrozza, & Dario, 2007; Zollo, Siciliano, De Luca, Guglielmelli, & Dario, 2005). Figure 1 depicts a desired vision of robotic development for manipulations. Obviously, one natural way to solve the above problem is utilizing high-precision sensors to acquire the relevant information (Erdmann & Mason, 1988; Qiao, Wang, Su, Jia, & Li, 2015; Sun, Hollerbach, & Mascaro, 2009). For instance, due to the restricted capabilities of the human hand, pick up or injection to a single cell are often implemented by robots in the medical researches. In addition, automated assembly tasks require high precision and quality for the production consisted of micro components. For a relatively complete coverage of the high-precision robotic applications, readers are referred to the literature and references therein (Murray, Li, Sastry, & Sastry, 1994). Generally speaking, achieving high precision for robotic manipulation can be categorized into two main types: the high-precision sensing methods and the sensor-less methods.

\subsection*{1.1. High-precision sensing methods}
Traditionally, in order to achieve the high-precision manipulation, one primary method is utilizing the high-precision sensors with rich sensor information. Figure 2 depicts a schematic representation of the high-precision robotic manipulation assisted by the high-precision sensor feedback. To date, extensive related researches have been carried out and thereby obtained fruitful scientific results. In Murthy, Stephanou, and Popa (2013), an articulated four axes micro robot with tiny-sized high-precision positioner is proposed for nanoscale applications. In Chen, Carbonari, Canali, D’Imperio, and Caninella (2015), a dexterous gripper with high-precision sensing is developed for complicated manipulation tasks. In Xie, Wang, Feng, and Sun (2015), a group of vision sensors are utilized in the designed system to achieve paring manipulation of biological cells. In Liu et al. (2015), a six-axis force/torque sensor is equipped to a robotic fingertip. In Huang, Yamakawa, Senoo, and Ishikawa (2014), a high-speed camera is fused with a high-speed actuator...
to achieve fast peg-hole alignment. Human can be seen as a low-precision system from the aspect that we cannot measure a precise value for the visual, force and other information we acquired. However, human can still fulfill high-precision tasks and the performance will evolve during their learning process (Qiao, Li, Yin, Wu, & Liu, 2016). At the hardware level, the tasks impose the minimum precision requirements for sensors, which may increase the initial cost and reduce the robustness and reliability. Furthermore, for some specific applications, it is even impossible to measure enough needed information.

Based on the aforementioned consideration, researchers started to explore, of the original intention, if it is necessary to pursue all high-precision sensor information, which gives rise to the so-called sensor-less manipulation problem.

### 1.2. Sensor-less methods

Invoking by the approaches of employing compliance in assembly tasks, an alternative sensor-less approach has proved that desired accuracy requirements can be met, and has achieved remarkable success and resulted in an increasing research interest. In Whitney and Rourke (1986), the mechanical behaviour and design equations of remote centre compliance are proposed to be a guide for the proper use of these compliant devices. In Goldberg (1993), an effective algorithm is provided to orienting a polygonal part without sensor feedback.

Succeeding the remarkable developments in theory and applications, one of the efficient methods regarding these issues is the ‘attractive region in environment’ (ARIE). The concept of ARIE was inspired by the application scenario in peg-hole assembly operation. It is known that high-precision peg-hole assembly is a very difficult task, due to the strict requirement for the sensing system, and the contact information of the parts cannot be accessed directly from the real environment (which is far different from simulation). Therefore how to achieve high-speed and high-precision assembly is a key problem in manufacturing. In the previous work, Qiao et al. found that during the process of inserting a round peg into a round hole, if the rotational angles of the peg are fixed, then all the available positions of the peg will form a special constrained region. In this region, the peg can be pushed into the lowest point with a simple, state-independent input. When the state converges to the lowest point, it means that the state of the system is stable, and the uncertainty of the system is eliminated. Furthermore, the ARIE is later on discovered in robotic grasping and localization tasks, and is found widely existing in the configuration space of the robotic systems. Figure 3 shows some of the attractive regions in environment existing in the robotic assembly and grasping systems. Based on this novel concept, high-precision tasks in assembly, grasping and localization can be achieved without sensor information. In Qiao et al. (2015), the mathematical definition of the concept of ARIE was discussed, and the condition of the existence of ARIE in different configuration space was analysed. In Li, Wu, and Qiao (2015), the compliance of human hand was discussed and attempted to port to the robotic systems.

More precisely, the ARIE is defined in the configuration space of a robotic system. The configuration space is the set of states of the system. In such space, the available region of the states can be represented by a certain form of ‘constrained region’, which means that the states of the system are limited by some constraints formed by the system, such as the shape, texture and the material of the parts. If the initial state of the system is within some range of the constrained region, and if there exists a state-independent input which will push the state of the system to a global stable point of the region, then the constrained region is an attractive region in environment. As a result,
Figure 3. The attractive region in environment in different applications: (a) round-peg-round-hole insertion; (b) convex-peg-convex-hole insertion; (c) dual-peg-hole assembly and (d) grasping for parallel 4-pin gripper.

the mathematical framework of ARIE can be presented as follows.

Definition 1.1: Assume that the state of a system can be characterized as
\[ \frac{dx}{dt} = f(x, u), \]

where \( x(t) \) is the state of the system. For all \( x \) in the region \( \Omega \), if there exists a state-independent input \( u(t) \) and a certain function \( g(x) \) satisfying that

- \( g(x) > g(x_0) \) when \( x \neq x_0 \),
- \( g(x) = g(x_0) \) when \( x = x_0 \), and
- \( g(x) \) has continuous partial derivatives with respect to all components of \( x \), then the system will be stable in the region \( \Omega \), which is called the ARIE.

According to the definition, ARIE can be considered as a kind of constrained region, from any point of which the uncertainty of system state can be eliminated by a state-independent input. It should be pointed out that the key idea of an ARIE-based method is to find in which configuration space of the system the ARIE exists, and to find or construct a state-independent input to push the state to the lowest point.

From the above sensor-less methods for achieving high-precision manipulations, it is noteworthy that although environment information is not directly taken in the design procedure, it has played an important role and is potentially needed to assist in the relevant tasks. Figure 4 shows a schematic representation of the high-precision robotic manipulation assisted by environment information. However, it should be pointed out that there exists a trade-off between strategy complexity and accuracy from the application point of view, which still limits the further implements in most real-world applications. Moreover, the flexible-based mechanical designs should also be provided in these sensor-less situations.

1.3. Fundamental challenges

From the prior results, it can be found that, so far, there still exists a considerable gap between the high-precision sensing and the sensor-less methods. The key barriers can be summarized as threefold: (1) Firstly, as noted above, increasing the assembly precision while decreasing the overall complexity of assembly strategies and sensors is one of the most pressing matters. (2) Secondly, effective methods should be explored further to obtain the relevant complete and the required data for assembly by incomplete or limited sensor information from the sensors and the environment. (3) Finally, it is worth mentioning that how to achieve assembly or robotic manipulations with more flexibility in more general scenarios still remains open and unsolved. Unfortunately, to the best of the authors’ knowledge, few effective research results are available so far, and the aim of this article is to make one of the first steps to shorten such a gap.

Compared with the aforementioned strategies, this article focuses on establishing a novel bio-inspired co-sensing framework in terms of the constraints imposed by the environment. The main contributions of this paper can be summarized as follows: in this framework, high-precision manipulation can be achieved by utilizing simple and coarse sensing data, which can be considered as a
compromise method. One of the distinguishing features of the established framework is the constrained region in environment (CRIE), the key idea of which is the integration of the relaxed constraint and the coarse sensor information. In the following sections, theoretical details of the CRIE are provided along with experimental tests and validation results.

2. Co-sensing with CRIE

Attempts to bridge the existing gaps between high-precision sensing and sensor-less sensing are always challenging, but the efforts can lead to encouraging results. It is well known that although we human beings are not with the high-precision sensory organs during the evolution, numerous sophisticated operations can be performed successfully by us to some extent. Therefore, a nature question arises: How do we easily solve these problems that are incomprehensible for robots? Obviously, seeking and understanding the answer to this question would greatly help in the robot designs. Consequently, by careful observations of ourselves, the following interesting findings are presented.

2.1. Bio-inspired flexible adjustment strategy

Let us review the course of inserting a key to a lock, which is very common in daily life. Roughly speaking, there are two main steps for human: we first find the approximate position of the keyhole, then adjust the direction of the insertion force. Surprisingly, no accurate information is acquired for human to complete this operation. However, this seemingly simple task is still one of the difficult operations for most robots, which brings more deep thinking into biological mechanism.

It should be pointed out that the ability to deal with complex real-world environment in a flexible manner is one of the most striking features of human beings. Based on different types of objects, various movements could be executed precisely and promptly. Even with limited or coarse sensor information, we can plan and execute proper motions such as grasping and other manipulations. Among many factors that are contributing to the success of such complicated tasks, two aspects are especially highlighted: sensory information and movement control.

(1) Multiple sources of sensory information. It is worth mentioning that there are few sensory organs with very high precision of human beings during evolution, which is partly due to the environment constraints. As a result, although the relevant precision of our sensory information is coarse, we can integrate these multiple sources of information in an optimized way, such that the needed information can be obtained for high-precision manipulations (Clower et al., 1996; Elliott et al., 2010).

(2) Flexible strategies on movement control. Based on different types of sensory information, we can utilize flexible control strategies for various movements. Moreover, it should be pointed out that these behavioural flexibilities are optimal for us during evolution, which can help the human beings survive and develop in the long history (Cisek & Kalaska, 2002; Fiehler, Burke, Bien, Röder, & Rosler, 2009; Karl & Whishaw, 2015).

These biological evidences have revealed the relation of the environment constraints and the coarse sensory information and high-precision manipulation, which can also promise to support and enhance manipulations of the robots.

2.2. Definition of CRIE

The CRIE is a new framework in the configuration space of a robotic system. The main idea of CRIE is the integrated framework of relaxed constraint and the coarse sensor information. The former is passive constraint which is formed by the environment, and the latter is ‘active constraint’ which is captured by the sensing system. The passive constraint can be seen as part of the ARIE, which cannot be utilized directly. With the combination of active constraint, the constrained region is completed and the uncertainty of the system can be eliminated. It is known that there are many constrained regions existed in the configuration space of the system. However, not all of the constrained regions formed by the environment are complete enough to be used for strategy investigation for sensor-less method. But these constrained regions are still useful since they provide part of the contact information.

**Definition 2.1:** Assume that the state of a system can be characterized as

\[
\frac{dx}{dt} = f(x, u),
\]

where \( x(t) \) is the state of the system and \( u \) is the input to the system. The state of the system \( x \) can be divided into two parts: \( x_c \) and \( x_s \). \( x_c \) is the set of states which are constrained by the environment:

\[
x_c \in \Omega_c \subset \mathbb{R}^m,
\]

where \( \Omega_c \) forms an ARIE, or there exists a point \( x_0 \in \Omega_c \), a real number \( \epsilon > 0 \), and \( \Omega_c(x_0, \epsilon) \subset \Omega_c \) which forms an ARIE. And \( x_s \) is the set of states that are cognized by the sensors:

\[
x_s \in \Omega_s \subset \mathbb{R}^n.
\]
In detail, $x_s$ can be further divided into two parts: $x_{sg}$, which represents the global information (such as in which step of a task) of the system, and $x_{sl}$, which focuses on local information (such as pose and contact) of the system. And the relation between $x_{sg}$ and $\Omega_c$ can be expressed as follows:

$$h : x_{sg} \rightarrow \Omega_c.$$ 

On the other hand, $u = u_p + u_a$ is made up of two parts,

$$u_p = U_1(x_{sg}),$$

which is the primary input to push the $x_c$ to the stable state, and

$$u_a = U_2(x_{sl}),$$

which is the secondary input to adjust $x_c$ to speed up its convergence.

For a certain task, the region $\Omega = [\Omega_c, \Omega_s]$ forms the task space, and for each $x_{sg} \in \Omega_s$, there will be a corresponding $\Omega_c$ or $\tilde{\Omega}_c(x_0, \epsilon)$ that forms an ARIE in the configuration space. If there exist state-independent input $u_{\|}$ and state-dependent input $u_{\perp}$ in $\Omega_c$ the system being stable, then region $\Omega$ is defined as the CRIE.

Two tasks are considered as examples, which are depicted in Figure 5 to illustrate the idea of CRIE.

In task 1, a key is inserted into the keyhole of the lock by a robotic arm. In the first stage, the vision system locates the initial pose of the key and available region for it. In the second stage, the robotic arm inserts the key with a state-independent input $u_p$, and then a state-dependent input $u_a$, which considers the contact force and torque during the insertion process, and is also provided to make better use of the environment constraint and prevent the manipulation from jamming. Combined with the constrained region formed by the key and keyhole, the key will be inserted gradually, with a human-like adjustment action.

In task 2, a cup of water is moved to another empty cup by a robotic arm. In the first stage, the vision system locates the initial pose of the cup with water, and decides the grasp configuration of the robotic hand. In the second stage, the robotic arm pours the water to the empty cup with a state-independent input $u_p$, and then a state-dependent input $u_a$, which considers the contact force and torque and vision information during the process, is also provided to control the flow rate of the water and prevent the water from spilling. In fact, as depicted in Figure 6, CRIE can be considered as a more common case than the ARIE, and is more feasible.

To this end, it is worth mentioning that the implementation of visions and related technics for robotics has begun to grow and has boundless prospects in a wide range of manipulation tasks. Therefore, this combination with CRIE has great theoretical implications and potential engineering applications for achieving high-precision manipulations with simple coarse sensor information. Figure 7 depicts a schematic representation...
Figure 6. The process of utilizing the CRIE-based method to achieve robotic manipulation tasks. (a) In a robotic manipulation system, there may exist some CRIEs in a certain configuration space $C_1$ formed by the states of the system. (b) With the aid of coarse sensor information, an optimal region will be approximately determined in $C_1$, and then combined with the relaxed constraint the state will converge to a stable point. (c) Based on the global sensor information, the system will switch to the next configuration space $C_2$ to further eliminate other errors of the system. (d) Finally, the manipulation task will be achieved when all of the configuration spaces of the system are utilized and the errors are eliminated.

Figure 7. Robotic manipulation assisted by co-sensing feedback.

of the high-precision robotic manipulation assisted by co-sensing feedback.

3. Illustrative examples and discussions

In this section, without loss of generality, four cases where peg-in-hole assembly are achieved using different methods will be discussed to illustrate the effectiveness and benefits of the framework of CRIE. To simplify the problem and focus on the key idea, the round-peg-round-hole insertion in automatic manufacturing is taken as the example.

**Ideal case:** In the ideal case, the axis of the peg and that of the hole coincide, and there are no translational or angular errors in the pose of the peg. Therefore, the insertion task can be achieved by a constant input along the rotational axis of the hole, as depicted in Figure 8.

![Figure 8](image)

However, it is noted that in the real process of peg-in-hole assembly, there will always exist translational and angular errors, which may lead to certain jamming or damage of the parts.

**Assembly with high-precision sensors:** In this case, the error will be eliminated with the sensor feedback. As depicted in Figure 9, there exist some errors in the pose of the peg within an initial error range. In the assembly process, visual sensor and force/torque sensor will be used for the pose correction: (a) For visual sensor, the pose of the upper surface of the hole and that of the peg will be measured by image processing methods, and then the translational error and rotational error will be calculated
The peg-in-hole assembly with high-precision sensors. The peg may be jammed during the insertion process, and the error will be eliminated with high-precision sensor feedback.

Based on these measured values. Finally, the peg will be moved and rotated according to these calculated values to achieve the insertion. (b) For force/torque sensor, when the peg touches the hole, the contact force/torque will be detected by the force/torque sensor, and then the contact type will be recognized based on the contact force patterns. Finally, the peg will be moved and rotated according to the detected pattern to achieve the insertion. In both the cases, the precision of the insertion is of high dependency with that of the sensor deployed in the system, and in most cases a relative big error caused by the turbulence may lead to system failure since the generalization ability is limited.

Assembly with ARIE-based method: In this case, the error will be eliminated with the constraints formed by the physical environment. As depicted in Figure 10, there exist some errors in the pose of the peg within an initial error range. If the peg is rotated by a small set value (e.g. 5°), then there will be a 6-D ARIE available in the configuration space of the peg. If the rotate angles of the peg are fixed, the ARIE will be reduced to 3-D, and it can be used to eliminate the initial error with a constant input. When the three-point contact state is achieved (which is the only and stable state in the 3-D configuration space of the round peg), the peg can be rotated back step by step, and finally the insertion will be achieved. It should be noted that in this case, the larger initial error range can be endured than that of the method with high-precision sensors.

Assembly with CRIE-based method: In this case, the error will be eliminated with the constraints and coarse sensor information. As depicted in Figure 11, there exist some errors in the pose of the peg within an initial error range.

Firstly, the visual sensory information is utilized to locate the approximate position of the hole, and then the peg is rotated by a given value, and it is then ‘pushed’ into the hole with a constant input. Meanwhile, a state-dependent input is also applied to the peg, which corresponds to the contact force/torque between the peg and hole. In this case, the peg-in-hole assembly system acts like a human worker, who does not possess high-precision motion ability in nature but can achieve high-precision manipulation tasks. The compliance and flexibility are both improved.
when environment constraints and sensor information are joined together.

From the above results, it can be seen that there is the least method and structural complexity in the ideal case. However, in real applications, there will always be some errors, which will fail the assembly task. An intuitive way to eliminate the error is to increase the precision of the system, which means high-precision sensors should be deployed to the system to acquire accurate position and orientation of the peg. The high-precision sensor information will be used as feedback to form a closed-loop system, and the errors will converge to zero if the system is stable. An alternative way is to decrease the demand of the system for high-precision information. It is known that we human can perform many high-precision tasks with our bare hands, and it is clear that these tasks are not achieved by the precision of our hands (sometimes the more the focused one is, the more the hand trembles). In the ARIE-based method, the precision is compensated by the constraints formed by environment, but strategies to wisely utilize these constraints should be carefully designed to achieve the whole assembly task. A defect of this method should be taken into consideration that once the state of the system diverges severely, it can hardly recover without sensor information. A synthetic outlook is then adopted about the issue of achieving the high-precision assembly task. In the CRIE-based method, an intensive imitation of the mechanism of human hands is developed. The constraints formed by environment are still necessary, and meanwhile some coarse sensor information is integrated so that the system ‘knows’ more about ‘where it is’ and ‘what it should do’. In other words, the robust of the system is improved. It can be seen that the CRIE-based method is a trade-off of effectiveness, complexity, cost and so on compared with the sensor-based and ARIE-based method. A qualitative comparison of the different schemes is shown in Figure 12.

It can be found that our proposed method has considerable advantages and can help researchers for the protocol design of robots. It can be verified that the developed CRIE strategy with relaxed constraints and coarse sensor information can be considered as a compromise method with distinguishing advantages.

4. Conclusions

This article described a bio-inspired framework that allows high-precision manipulations by using only simple coarse sensor information. This is primarily motivated by the need to resolve the precision conflicts between sensing and actuating capabilities of robots. After investigating the mechanism of human operations, a new framework of CRIE has been proposed and discussed. Instead of chasing high-precision information, the key feature of CRIE is the integrated utilization of the coarse sensor information and relaxed constraint, which is more applicable in the applications. More importantly, the developed methodology along the CRIE can be directly applied with the existing vision technologies. Under this regard, the effectiveness of our proposed co-sensing strategy has been further demonstrated in a peg-in-hole assembly scenario from a dynamic point of perspective. It is

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**Figure 12.** A comparison of different sensing methods proposed in this paper. The items on the left: the higher, the better; the items on the right: the lower, the better (the points on the y-axis are with qualitative representation of high and low).
believed that the theoretical findings in our article can indeed augment the ability of robots with coarse sensors to accomplish high-precision manipulation tasks. As a work in progress, our future study is focused on the generalization of the framework in the related fields of manufacturing and robotic engineering. The conditions of utilizing CRIE will be discovered with more details, and efforts will be made on how to simplify the process of strategy design for such a robotic manipulation system. Moreover, the proposed CRIE framework would be utilized in the robotic location, grasping and assembly scenarios in the real-world applications, where high-precision manipulations are required.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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