Assembly robotics research: a survey

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ASSEMBLY ROBOTICS RESEARCH: A SURVEY

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Abstract

The authors provide a general survey on assembly robotics research. First, we give a brief account of robots for assembly, and methods of design for assembly. In what follows, we elaborate on assembly-related issues together with assembly control methods and strategies. Importance is attached to wrist-based methods and dynamic assembly. Some research directions of value are suggested.

Key Words

Robotic assembly, design for assembly (DFA), assembly control, dynamic assembly

1. Introduction

Almost every product includes an assembly process. Assembly operations consist of electronic or mechanical tasks or even tasks like product labeling. Typical assembly work includes nut screwing, clothing sewing [1], furniture assembly by a variety of adhesives, glues, staples, or screws [2], and medical application of hip implant insertion [3]. Assembly operation is labour intensive, absorbing a large share of the direct labour costs, and so robotic assembly offers an effective solution. Statistics [4] indicate that for 17 main robot-using countries, robots for assembly account for 34.5 percent of the total followed by welding at 23.9 and machining at 10.3 percent.

Robotic assembly has been widely used in electronics. Most high-volume circuit board assemblies consist of placing the connecting leads of components into holes spaced on a grid of 2.54 mm (0.1 in.). The assembly systems need to do pick-and-place operation and are sufficiently accurate. There are many successful methods: high-speed axial, DIP and radial component insertion systems. Recent research focuses on non-auto-insertable or odd-form component assemblies [5], nonstandard component insertion [6], and higher density assemblies [7].

Mechanical assembly is a complicated unstructured process. The peg-in-hole insertion represents a fairly large percentage of industrial assembly, and has received most attention. Although this topic was surveyed a dozen years ago [8], we overview the advances in assembly robotics with a focus on mechanical peg-in-hole insertion.

This survey is organized as follows. In Section 2 a brief account of robots for assembly is given. We introduce some popular design for assembly (DFA) methods in Section 3. Assembly control and related techniques are the focus of this survey, and are discussed in Sections 4–7; we elaborate on various wrist-based methods. dynamic assembly is presented as an important aspect of assembly robotics in Section 8. In Section 9 we propose some areas deserving further research. Owing to limited space, coverage is extensive rather than intensive.

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2. Robots for Assembly

For assembly tasks, dedicated assembly robots are generally more efficient than general-purpose robots. The most famous assembly robot is selective compliance articulate robot arm (SCARA) [9]. SCARA is a 4-DOF robot adopting built-in compliance that can only correct laterally, and is suitable for the assembly task of "down-to-up" mounting that forms most existing work if the product design is suitable. By the simple and stiff mechanism and by the "virtual cam curve control method" it can move at a very high speed without any vibration and works with high performance. caresian-type robots are also widely used in electronics assembly as well, there are robots for odd-form electronic component placement [10], for assembling flexible items like wiring harnesses [11], for screw-driving [12], and for construction assembly [13]. One can always locate many commercially available high-performance and high-speed assembly robots for various applications in the journal *Assembly*. The following assembly robots represent the state of the art of robots for assembly.

1. *Autonomous Assembly Robots:* One of the objectives of assembly robots is work autonomy, which is based on artificial intelligence techniques [14–15]. Autonomous mobile assembly robot systems are capable of operating autonomously at various assembly stations within assembly cell according to an *a priori* given assembly plan.
2. *Parallel Assembly Robots:* Due to its superiority, many robots for assembly shift to using parallel structure [16], which combines the advantages of serial and parallel designs. The conventional parallel structure is the 6-DOF Stewart platform and its various versions [17, 18]. There are many fully parallel 6-DOF robots suitable for assembly works, such as those in [19–22]. The author of [23] proposed a complete versatile design methodology for parallel robots.
3. *Direct-Drive Assembly Robots:* Direct-drive manipulators [16, 24] use high-torque low-speed motors directly coupled to loads, thus substantially eliminating friction from gearing. This avoids the inertia associated with "big" joint. This type of robot combines very high speed and load-carrying capacity. The primary benefits of the design are speed, accuracy, reliability, and ease of repairs.
4. *Cooperative Assembly Robots:* For precision assembly or heavy-duty work, the cooperative assembly robot is a better choice [25–27]. These can be operator-robot cooperative [25], dual arm cooperative [26], or robot-robot cooperative [27].

5. *Micro Assembly Robots.* Microcomponent assemblies require new dedicated micro-robots. They must have submicron resolution and/or precision, and be reliable, rigid, and compact. In [28] design guidelines for microrobots were proposed. There are many prototypes [29, 30, 22]. Parallel structures are most promising for microbotics [22, 28]. The accuracy of such mechanisms could be useful in meeting future challenges.

3. Design for Assembly

Due to the need for massive computational/processing power, the flexibility of the current assembly robot comes at the expense of speed. From an application perspective, DFA is somewhat fruitful. Furthermore, the limitations of a particular assembly technique can be compensated for in product design. The problems surrounding DFA were examined in one study [31]. One most important obstacle to assembly automation is that the product design is generally not assembly oriented.

Assembly process consists of feeding, handling, mating, inspecting, special operation (deburring), and adjusting. DFA should facilitate these operations. A systematic design procedure is an iterative design procedure, the central theme of which is the avoidance and simplification of assembly operations while maintaining sufficient proper flexibility to ensure high utilization, high productivity and consistent high quality.

The conventional approach is called the "axiomatic method" [32–34]. This method is simply a set of design guidelines derived from years of experiences in design and assembly operation. The author of [33] identified 10 desirable features of product design, including minimum number of component parts, unidirectional insertion of parts, stackable assembly, standardization of similar parts within the assembly, minimal use of flexible parts, and compliance such as chamfer to facilitate assembly. In particular, [34] assigned scores to each of the design axioms in a subjective manner in an effort to make the axiomatic method more evaluative. In conventional DFA methods, the redesign is entirely left to humans. In [35] a quantitative shape metric "feedability" for planar parts was introduced, based on a stochastic parts feeding algorithm. This relates one aspect of assembly cost directly to part geometry. This method can be used to guide the redesign of part geometry subject to geometric constrains: then geometric redesign advice is possible [36, 37]

Currently, the method pioneered by [38] is thought appealing. In this approach a product is analyzed by various easy-of-assembly criteria, organized with charts of scores, and a tabulated score is used to calculate a "design efficiency ratio." This metric is empirically based on an engineering time study method. Then a redesign is proposed with the help of the score table.

4. Several Issues Concerning Assembly Control

During the assembly process, uncertainties concerned with inaccurately positioned workpiece and manufacturing tolerance, and absorption of the reaction force, necessitate diverse, flexible functions in the robot system. There are two main phases for peg-in-hole assembly: searching for the hole, and insertion operation. Fundamental approaches to this problem are categorized into three different methods [8]: passive accommodation, active compliance, and compound accommodation. Accommodation is defined as a process in which the contact forces between parts modify their relative position or motion. In passive accommodation systems the position correction is generated by the contact forces themselves, whereas in active ones the forces are a source of information from which the positions are calculated.

4.1 Sensing

Sensing is indispensable in active assembly systems. Sensors can be used to monitor and control the process, to provide a certain amount of adaptability for deviations, and to enable control of the robot. Further, sensing can provide flexibility through the ability to distinguish randomly presented parts, and can enable assembly of different products on a single station. Another task for sensing systems is in-line inspection of parts and subassemblies.

Force sensing[1] is one highlight of assembly robotics. It can be categorized into joint sensing and wrist (gripper) sensing. Joint sensing measures the Cartesian components of force acting on a robot joint by using strain-gages, or simply by measuring the motor current. A more direct and precise way is to use force-sensor functioning as a wrist, integrated into the gripper or forming part of a fixture. The 6-DOF wrist or finger force sensors are widely studied, and there are many commercially available high-performance ones. They can be instrumented with strain-gages, optical transducers, or linear voltage differential transformers (LVDTs) [39, 40]. Most force sensors employ compliant structures that possess good performance, such as decreased coupling.

Wrist and finger sensors can be the same in principle, with the difference merely that the finger sensor is so small in size it can be integrated into fingers. The existing force sensors are mostly located at the wrist. Wrist force sensors are incapable of detecting small changes of force on the end-effector because the weight of the hand itself masks the change of payload. Finger force sensors are in direct contact with the object and thus provide more precise information. The small size to be built in the top part of fingers makes for simple structure. Finger force sensors, however, make it very difficult to obtain independent measurement for each cell due to the cross-task effect. Some researchers have tried to solve this limitation by using capacitance detector and neural network signal-processing system [41].

[1] In this paper, "force sensor" measures force and torque.

When designing force sensors, one should adhere to such guidelines as trying to make the sensor capable of redundance in case of partial damage, and meanwhile minimizing hystersis. The reduction of hysteresis can be achieved by physical symmetry, including the mechanical mounting, or by machining the sensor from one piece of metal material.

Vision is widely used in assembly. It has the best sensors as well as advanced image-understanding techniques. Tactile sensing can effectively recognize a profile of an object with a complicated surface in an environment where visual sensing cannot work well due to poor visibility and shows great promise in assembly, based on extensive research on the multi-fingered hand. The proximity sensor is a reliable sensor used for positioning a robot gripper [8]. Ultrasonic or acoustic sensor is very popular in autonomous assembly robot navigation; they can also be mounted on a gripper to range-find between the gripper and the surface of an object, or even be used to listen to characteristic noises emitted during the act of assembly [42]. Slide sensor is useful as the robot changes its speed.

4.2 Sensory Data Integration

With increasingly complex assembly tasks being preformed automatically, multiple sensors are used to acquire information. Sensing can be grouped into four stage of information acquisition: far away, near to, touching and manipulation [43], with each differing in the type of sensors and the nature of the information obtained. Thus, a problem arises about how to integrate data from several independent sensors. [44] proposed a hierarchical robot-sensing strategy as one solution. At least one sensor is used to perform the necessary control for each step of a robot function, and these sensors are used successively. Multiple sensor readings complement each other. [43] adopted the idea of fusion to merge two or more separate items into a single entity. [45] employed the concept of error probability vectors to construct a formal mathematical framework to verify and recover sensor errors that help in sensory decision making. [46] treated the dynamic detection of small, geometrical errors on assembly workpieces using accelerometers, force sensor and electrical contact indication, in order to develop a static-dynamic assembly model that includes all three categories of errors—dimensional, geometrical, and surface errors. [47] designed a sensor integration system for a large full-integrated flexible assembly machine, using the concept of virtual sensing to provide sensory data at an appropriate level of abstraction to the machine supervisor, which controls execution of the assembly tasks.

4.3 Multifingered Hand versus Wrist

Hands (grippers) and/or wrists are indispensable for robotic assembly. Grippers are tailor made for a particular type of task. For various tasks, one solution is to provide individual grippers arranged in racks within reach of the robot arm. [48] addressed the use of self-changing gripper characteristics to permit the grasping of a wide variety of geometric shapes with a limited number of different gripper types by means of the geometrical similarity of parts. Generally, changing grippers leads to an increase in production time.

Light-weight and delicate end-effectors are increasingly in demand due to the rapid development of light-weight manipulators and microassembly and micromanufacturing. There are many prototype end-effectors for microassembly based on shape memory alloy (SMA), the piezoelectric effect, stick-and-slip effect, and bimorph beam actuation ([22, 49, 50], to name a few).

The human hand is an ideal, powerful tool for assembly operations. The multifingered hand aims at human mimicry, that is, trying to emulate the operation morphology of the human hand and to design for anatomical consistency with that hand. Experiments in [51] demonstrated the feasibility of using a multifingered hand for assembly operations. Currently, research on the multifingered hand is very active, and there are many prototypes available [52–56]. However, many problems with the multifingered hand remain to be solved; for instance, the impact forces at the instant of grasping a rigid object affect the functioning of fingertip sensors, hard fingers cannot securely grasp an uneven-surface object, and repetitive strains are included within the fingers throughout a manipulation task. Soft materials for fingertips were explored to solve these problems [57], but practical grasping strategies have yet to be developed. [58] tried to combine task-oriented hand control and strategies to solve peg-in-hole tasks, to the capabilities of dexterous grippers to the requirements of tasks. This approach is useful for a large class of tasks.

The wrist is an area at or close to the point of attachment of the end-effector to the robot. Wrists have gained a noticeable niche in robotics research, and a broad literature of theoretical work, mainly on avoiding singular positions and on practical designs, is available. General-purpose multi-fingered hands are far more versatile but too complex for industrial automation. The selection of a robotic wrist or fingers involves a trade off between dexterity and strength. Many factory tasks are amenable to automation, provided that they fit into the "wrist" category. From an industrial viewpoint, for heavy manufacturing tasks, an active wrist with passive fingers may actually perform better than a gripper with active fingers [59, 60]. Thus, a wrist is sufficient for typical mechanical peg-in-hole assembly. In this context, we focus on wrist-based assembly methods.

4.4 Coarse-Fine Manipulation

Endpoint sensing accuracy is limited by the resolution of a robot (typically 100 um). The concept of micromanipulation involves attaching to the end of a relatively coarse robot manipulator a device capable of finer precision, which is particularly suitable for precision assembly. In the coarse-fine system, the coarse manipulator serves merely as a position-control transportation system, whereas the wrist can be position, compliance, or force controlled, and actually carries out the work. The system has essentially the same workspace as the coarse manipulator and the same resolution and disturbance rejection ability as the fine manipulator, and when its endpoint contacts the environment, it presents the fine manipulator's mass and moments of inertia. The system is inherently more stable in regulating interface forces than a conventional robot system. This combination improves the effective precision by several orders of magnitude, and avoids the resolution limitation of the robot. Most present investigations assume this form.

4.5 Bracing and Stability

Mechanical bracing of end-effectors using "jig hand" fixtures was treated analytically and experimentally in [16, 62]. By sacrificing one or more DOFs, we can greatly improve the load capacity, stiffness, and relative part positioning accuracy. [63] used the redundant DOFs of the coarse-fine system to brace either the coarse or fine manipulator for precision assembly. The bracing can be real if used for the coarse manipulator, or virtual if used for the fine manipulator. This requires sufficient bandwidth for this method to succeed. Results from a real implementation of coarse manipulator bracing indicated that assembly error of a few um can be readily obtained, which is approximately an order of magnitude improvement over the unbraced coarse-fine case, and nearly two orders of magnitude better than those attainable by coarse manipulation alone. Meanwhile, bracing can induce improved stiffness as well as reduced susceptibility to vibrations.

When a fine manipulator is attached to the endpoint of a robot, the reaction forces due to the fine manipulator motion can interact with the coarse robot controller or can excite the structural modes of the coarse robot and lead to a poor or even unstable performance system. The authors of [64] pointed out that a passive system remains stable at all frequencies when coupled with an arbitrary passive environment. The authors of [65] developed a simple, robust controller design based on equivalence and impedance matching. The method can achieve interface force regulation at bandwidths higher than the structural frequencies of the macromanipulator with minimal knowledge of the structure. Other research [66] presented a general robustness criterion for designing a controller for a redundant coarse-fine manipulator. The controller for the fine manipulator can be designed independently of the coarse manipulator, as long as the criterion is satisfied.

5. Passive Accommodation

The structure of a multijoint robot itself has a certain built-in compliance, which facilitates assembly in a certain range. One famous compliance method is SCARA [9]. Most robots, however, have limited compliance, and for different position and pose the compliance is hard to determine; special passive compliance devices are preferred.

Passive accommodation employing the concept of remote centre compliance (RCC) is the most famous and successful approach [67]. the authors of [67] provided a complete quasi-static mechanics analysis on compliantly supported peg-in-hole assembly [68], and extended this analysis to any assembly modelled in the plane, including multiple insertion.

The RCC device was initially of all-metal design, later evolving into using elastomer shear pads as shock mounts or limited motion bearing. Researcher have proposed a design in which shear pads are arranged in a push-pull configuration (Fig. 1), possibly with a little compressive preload. whatever direction the RCC deflects, its response is dominated by a pad that is in compression. This avoids the severe softening of a pad that causes the compliance centre of an ordinary RCC to retreat towards the body of the device. In addition, the push-pull arrangement almost completely eliminates the stiffness nonlinearity of the pads. The RCC also has considerable axial tensile strength, and the likelihood of pad tensile rupture is greatly reduced. [70] proposed an RCC mechanism constructed with rubber blocks made from sheets. The rubber blocks may be changed to achieve any desired compliance for different operations. The RCC consists of two portions: the upper one with three rubber elements in an equilateral triangle, and the lower one with eight elements horizontally in four sides of the cube connected to the axial stiffness.

Figure 1. Push-pull design for a shear pad RCC.

The aforementioned RCC structures are unreliable in assembly of rectangular and generally prismatic parts. A new strategy for nonaxisymmetric insertion was presented in [71–73]. [71] investigated quasi-static wedging of the three-point contact. It extended the wedging diagram [67] into three dimensions. Possibilities of wedges for fully started contacts — for example, the orthogonal configuration between square peg and hole — reveal virtual wedging among three contacts. The wedging space is described by the parameters of contact configurations. Initial orientation of the peg must avoid this wedging space. Based on the concept of orthogonal compliance, the spatial RCC (SRCC) was patented (Fig. 2). The SRCC consists of a conventional RCC in series with a screwed strip embodied as a mechanism for correcting errors in the azimuth angle. suitable torques and displacements are generated whenever a peg-hole contact force occurs. This SRCC transcends sensor-based control approaches to precision assembly of nonaxisymmetric parts, and jamming and wedging are avoided.

Figure 2. Spatial RCC.

RCC device has a compliance centre similar to centroid kinematically. The existence of compliance deteriorates the position control precision of manipulator. This problem can be alleviated by bracing some DOFs of RCC using proper device. The RCC wrists enable high-speed assembly without jamming or wedging; it must, however, be designed for a particular peg-hole geometry and weight and can only be applied to chamfered parts. The vibratory method [74–77] can implement a random search of a hole without an intensive search algorithm. the insertion force pushed the peg into the hole the moment the alignment is established. This method is useful for nonstandard, flexible or charmferless parts mating. It is often desirable to introduce small-amplitude random vibration or dithering during parts mating to overcome stiction contamination and burrs. Accordingly, end-effectors have been equipped with a piezoelectric or electromagnetic vibratory device [76]. Despite its known effectiveness, a typical vibratory assembly method tends to generate adverse impact forces between parts commensurate with he relative large vibratory motion required for reliably compensating position errors of arbitrary magnitude. [77] presented a neural network-based vibratory assembly method to reduce the mating forces and to expand insertion error range for prismatic parts. The interactive force is effectively suppressed by reducing the amplitude of vibratory motion, and the greater part of the relative positioning error is estimated and compensated by a neural network. Other methods include air-stream-assisted method and magnetic force method (for details, refer to [8]).

A passive, position-adaptive system does not need to make any change in a robot controller. This provides a reliable, fast, and relatively cheap solution. However, flexibility is low and accommodation error range is limited. Moreover, the robot must generate great power to press the peg into the hole. This method would reduce the repeatability of the robot.

6. Active Compliance

Increase of flexibility is accompanied by a sacrifice of rigidity. To increase flexibility, the basic idea is to reduce the mass of structure, allow structural vibrations to occur, and then use a controller to suppress these vibrations. Active compliance is based on sensing techniques.

6.1 Visual Control

Visual-controlled robots occupy an important position in assembly, mainly in the electronics and auto industries [78]. A vision system involves object recognition, feature extraction, and visual serving. Such a system provides the capability to visualize position and orientation, and thus can in principle handle and assemble parts presented in a variety of attitudes. Visual compliance can provide a cost-effective, flexible, and fast method of noncontact fixturing, eliminate the possibility of binding or scratching. Unlike force control, controllable motion is not necessarily along the normal direction on physical constraint surface. Visual-controlled robots can compensate for changes in their own physical structures and can be easily reconfigured to a new task.

Many assembly operations, such as electronic component insertion, are inherently positioning tasks, which have little or nothing to do with force compliance. These components are hard to describe by geometrical models and are often so small and delicate that it is not possible to design chamfer or other features to facilitate force compliance assembly. The requirement for contactless insertion precludes force compliance schemes, and necessitates continuous monitoring and correction of the position of the peg with respect to the hole during the insertion process. Visual control is especially suitable because a vision sensor has none of these drawbacks.

Binary imaging and gray-level imaging are two basic image-processing techniques. Binary imaging can only be used for the assembly of simple parts. Gray-level imaging has significantly higher resolution and extracts more information regarding the detailed geometry and orientation of a part. Several fundamental problems remain to be solved such as large processing time, focus, 3-D object recognition, and nonideal industrial lighting conditions. Applications of camera-based vision are still to be improved for precision assembly. Recently there has been some research into high-precision peg-in-hole assembly [79–81]. [79] presented a high-precision, self-calibrating insertion strategy using several optical sensors. The key to the strategy is the use of a fixed sensor to localize both a mobile sensor and the peg, while the mobile sensor localized the hole. Position errors were corrected dynamically during normal assembly operations. This method is as fast as RCC insertion and as flexible as active strategies. Some researchers are exploring fiber optics or laser beams to eliminate the limitations of camera-based vision [8].

6.2 Force Control

For mechanical assembly, parts are subject to contact forces and torques. Measurement of the force and torque provides the most reliable information for guiding the movement of the robot. Force control is a fundamental method in robotic assembly. [82] surveyed various force control methods. The force-feedback-based assembly method allows a comparably large positioning error in the case of unchamfered parts, and the insertion force can be drastically reduced as compared with passive method. The measurement and calculation of force and torque involved can be performed at such a rate that insertion of force sensing inside the feedback loop is possible. Force control can realize variable compliance operations crucial to many assembly tasks. However, the long assembly time, complexity, and expense of the force sensing system hamper its wide applications. In what follows, we detail various force control wrists.

6.2.1 Levitation Wrist

The levitation method provides many advantages over other active methods. It possesses such properties as precise positioning capability of a micron or submicron, high speed and acceleration, programmable compliance, absence of friction and wearing, and the resultant complete cleanliness. It has the drawback of high power consumption.

Hydraulic/pneumatic drive wrist and magnetic force drive wrist are the two main methods. Electromagnetic actuation has the advantage of being reliable, positionable, and easy to interface with computer systems. Disadvantages are its poor power-to-weight ratio. Hydraulic/pneumatic actuation, on the other hand, produces linear motion and has a very high power-to-weight ratio. However, although it is virtually noncompressible, accurate positioning still requires the use of precision flow and metering valves and a feedback control system, along with auxiliary fluid equipment. Hydraulic/pneumatic systems are not convenient to interface with a computer.

Magnetic levitation technique including magnetic bearings is most promising for future applications [83–95]. It is easy to implement active vibration control, force control, and to program compliance by alternating the control parameters of the magnetic bearing.

The most prominent of this kind of work is the magic wrist [83–85] (Fig. 3), which is a six-DOF parallel magnetically levitated wrist with the potential for unequalled performance in tasks requiring accurate positioning and small compliant motion. The full potential of this wrist can only be realized by control schemes that allow programmable positioning and compliance. The position and orientation of the wrist are obtained from an optical sensing system. Many simple and useful mechanisms can be emulated with the wrist by restricting DOFs. for instance, by allowing some rotational and some translational motions, an RCC device [69] is synthesized. Unlike conventional mechanical mechanisms, all these are selectable by program control in real time, and can be altered several times even within a single job cycle. a new model [85] can be used as force sensor, fine positioning device, and as compliant mechanism emulator, among other functions.

Figure 3. Flotor configuration: (a) at zero position and orientation, showing coincident stator and flotor framer; (b) displaced and rotated.

[85, 87] developed a five-DOF magnetically levitated wrist. [88–92] described a compact, two -or three-DOF fine-positioner capable of fast, extremely precise motion. [93] fabricated a three-DOF wrist in which the force is as uniform as possible in all directions. There are also other prototypes, such as a three-DOF magnet force wrist [94], and other applications of magnetically levitated wrist [95].

Early research on the levitation method focused hydraulic suspension wrists [96–98]. The variable compliance attainable from a pressured compliant system was utilized to control the parameters of the RCC device. A wrist using four hydraulic actuators to actively achieve RCC was presented in [97]. The wrist employed spherical springs with an adjustable stiffness and has five DOFs, being compliant in each direction except axial extension with programmable compliance whose centre of compliance may be located anywhere inside a restricted task-space region. [99] presented a new six-DOF pneumatic parallel fine-motion device while keeping essentially the same geometry and sensing system of the magic wrist; this device is capable of much higher steady-state forces. The device uses six pairs of externally pressurized mechanical bellows as a pneumatic suspension, and the complete symmetry of structure about the x-y plane and dynamic balance together with active cancellation of z-axis moment. [100] developed an air-bearing supported three-ODF high-performance fine positioner using a single three-DOF motor.

6.2.2 Serial Linkage Wrist

A conventional robot is of serial linkage structure. Serial structure has a highly developed theory and simple geometry. However, due to cumulative errors and poor rigidity, the maximum payload needs to be kept comparatively small to maintain the static accuracy. There also exists singular configuration with he loss of a DOF. When used as a wrist, they are generally rigid small manipulators [101, 102].

A macro-micro system [102] was proposed to realize trajectory control of a flexible manipulator system. This system has a flexible manipulator as a macro manipulator and a rigid small manipulator at the tip as a micromanipulator. [101] developed a six-DOF micromanipulator using six PZT actuators adopting a fuzzy-like variable gain feedback control system.

6.2.3 Parallel Linkage Wrist

The fundamentals of parallel or closed linkage structures have been established [103], and the modelling, control, and singularity of such structures have been widely studied. Their general advantages over their serial counterpart of noncumulative positioning errors, improved actuator load distribution, m compact structure, rigidity, increased payload, and rapidity. Further, the inverse kinematics problem is typically straightforward. Parallel structure may also have singular configurations, but it is a far cry from serial mechanism as it gains one or several DOFs [104].

The three-axis hummingbird mini-positioner is very impressive [105]. This five-bar parallel drive mechanism is unique for its dynamically balanced, symmetric actuator/linkage design. It can provide fast and accurate positioning of a low-mass probe tip on or above a nearly planar object. Peak XYZ accelerations reach 500 m/s^2, with positioning resolution under 1 um and a workspace of $13 \times 13 \times 1$ mm. Large workspaces can be partitioned into an array of cells smaller than or equal to its workspace, and it can be mounted onto a suitable large-area positioner, which moves the minipositioner between cells. The system weighs 950g and is nearly reactionless during X–Y motion to simplify integration with large-area positioners. It is especially suited to high-density electronics assembly and potential mechanical applications such as wire-bonding as well as optical applications such as laser beam positioning.

The authors of [106] developed a three-DOF parallel, pneumatically actuated ankle or wrist that consists of two platforms connected by three serial chains. [104] developed a six-ODF wrist driven by hydraulic cylinders. [107] constructed a two-DOF parallel wrist in which there is no passive compliant element. There are many other parallel structures suitable for light wrists such as the three-DOF wrist [108].

6.2.4 Active Accommodation Strategies

Apart from the foregoing wrist-based control methods, there are many active assembly strategies. (Early research was detailed in [8].) For high-precision chamferless peg-in-hole insertions, good strategies are more efficient than complete but complex models, high-precision mechanics or extremely accurate computations and control loops. For example, rotation is a common means to prevent jamming, and is effective in helping the search of the hole.

One popular method is to pretilt the peg relative to the hole to eliminate the ambiguity of the tilt direction of the peg [109, 110]. The assembly process is divided into three phases: the initial deliberate misalignment used to reduce the uncertainty of the robot positioning, the alignment process, and the insertion process. [109] presented a general strategy applicable to chamferless circular and three-dimension rectangular insertions. The strategy is to tilt the peg relative to the hole and place the bottom corner of the peg into the hole. Once the peg is in contact with the hole, the peg may be rotated while maintaining sliding contact with the hole by application of appropriate force until the opposite corner of the peg clears the top edge of the hole and the peg slides into the hole without jamming. [110] developed a general strategy based on hybrid force/position control that suits every assembly task having a plane of symmetry passing through the axis of insertion. The strategy i9s independent of the exact geometry of the components.

The capacitate guidance assembly technique is attractive [111]. Capacitance homing tends to reduce the complexity and precision requirements of the assembly machines and the assembled parts. Because homing is between mating surfaces, the surfaces only need be well defined. The large capture range of the method also reduces constraints on the initial configuration. The inherent high sensitivity stems from the fact that capacitors generate no noise. Capacitance homing procedure is practically time-limited only. [112] used noisy dynamics to explore the neighborhood of the insertion zone. The mean time required for the insertion grows logarithmically with the precision required to perform an insertion, which appears to be very efficient in high-precision mating.

[113] investigated the effects of scaling factors on assembly performance and presented a fast searching technique for large initial error based on the fuzzy rules. This technique consists of two modes: a fine compensation mode in case of small error and a coarse one in case of large error. The two modes are switched by heuristically adjusting the output scaling factors depending on the magnitude of errors. [114] presented a practical method for generating strategies applicable to assembly. The robot is endowed with the capability of learning corrective action in response to the force signal through iterative execution. The strategy is realized by adopting a learning algorithm and is represented in a binary-tree-type database.

Few methods have successfully overcome the ambiguity due to uncertainty. [115] proposed to move and rotate the peg from an area having many geometric uncertainties to a new area where signal from the force sensor is related to the deviation of peg and hole. For those unsurfaced parts, force signals are very noisy and erratic; [116] took positive action by actively shaking the end effector and observing the reaction forces to the perturbation in order to obtain rich, reliable information and to determine the direction of the part surfaces and guide the part correctly.

In the field of light robotics, the pieces often do not have any chamfer to guide the peg into the hole. [117] suggested inclining the peg by bending an elastomeric structure. This deformation will store enough energy to get a self-centring of the peg when it is set right again. The force sensor detects the locking of the peg at the opening of the hole and starts the alignment phase.

[118] proposed strategies based on the assumption that the geometry factor is dominant during assembly. The insertion depth and the tilt angle between the peg and the hole will be calculated and monitored to avoid wedging. [119, 120] presented strategies based on the good orientation accuracy in parts and in robot arms. [121] implemented joint-sensing-based assembly on a large compliance robot by allowing jamming and using toughness of this arm. [122] used the impulsive force to detect to adjust the position and orientation errors between two coordinating arms immediately after a contact occurs but before an insertion starts. There are also assembly strategies, such as for assembly in zero-gravity environment [123] and for a flexible beam mating with a rigid hole [124].

7. Compound Accommodation

Due to the merits and demerits of passive and active methods, the combination of force sensors and a compliant device can yield a flexible, fast, and reliable solution to the chamferless parts mating problem. In this method the passive device serves as a high-speed error absorber, whereas the active portion is in charge of measurement and control that can be suitable for long-term adaptive behaviour. Three basic strategies are available. (Although we categorize compound wrists by strategy, in hardware they can be used for any strategy the difference is merely in software.)

1. The information measured is used to adjust the pose of the wrist to nullify the deformed states [70, 125–128].

The instrumented RCCs (IRCCs) by [125, 126] are worth mentioning. They have many uses, including active accommodation for RCC static forces, on-line teaching contact sensing, error protection, adaptive control, and automatic touchup. [70] presented a hybrid position/force control for their RCC. a simple fuzzy controller was implemented in insertion for velocity assignment instead of checking exact force zones. [127] developed a wrist that uses rubber elements for compliance and damping, and a serial linkage, with potentiometers at each joint. This wrist is designed to partially surround the tool to reduce the distance between the end-effector and the tool. [128] proposed a device by integrating passive compliance into a three-fingered two-DOF hand. It provides a programmable passive RCC capability as well as a servo-controlled grasping capability within the same device.

2. Within allowable force limit, parts mating is by passive method; above this threshold, active method is used to reduce insertion force [129].

   [129] studied a five-DOF wrist with two active DOF driven by voice coil and three passive DOFs. [8] detailed the above two strategies based on previous literature.

3. The third strategy is to combine active and passive compliance in one organically, and alternate the active and passive operation by control [130–133].

   [130] developed a micromanipulator and the corresponding assembly strategy for insertion along arbitrary direction. It has four DOFs driven by four stepper motors. While being actuated by stepper motor, a joint is under active state to implement active accommodation accordingly; when not being actuated a joint is in passive state to realize passive compliance operation. This can be combined arbitrarily by computer.

Springs and dampers (such as spring-load pistons) can be easily coupled into parallel, platform (typically Stewart platform) based structures; thus these structures are suitable to construct passive compliant wrists [39, 40, 131–133]. The length variations of the pistons can be measured by LVDTs mounted along the pistons. Such wrists are practical force sensors. Based on the known spring constant and the piston length changes, force sensors are capable of measuring torque applied to the gripper and of monitoring transient forces applied, and are fast enough for real-time force computation.

8. Dynamic Assembly

Assembly robotics still cannot satisfy high production demands. As operation speed increases, intrinsic mass properties of the parts and the robot manipulator have more dynamic influence upon task performance. When rigid parts come into contact with each other, high-frequency impulsive forces, which are often higher than the bandwidth of the robot control system, act upon the parts. To overcome this disadvantage, Hogan [134] proposed the impedance control method to compensate inertia, damping, and stiffness simultaneously. If proper expected stiffness is guaranteed, one can determine the range of work frequency of the system by selecting the damping and inertia properties. For given stiffness and damping, as inertia impedance decreases, transition frequency and frequency range will increase. Active dynamic control can improve dynamic behaviour to some degree; however, it cannot change the intrinsic mass characteristic of the parts and the manipulator.

Recently, there has been much research into the dynamics of assembly process. [135, 136] proposed a dynamic passive RCC hand (DRCC) (Fig. 4) based on the concepts of generalized centroid and virtual mass. The DRCC can carry out high-speed chamfered peg-in-hole insertion. By considering the main process of peg motion as the quasi-static case and only the impacts as dynamic process, one derives only non-bouncing collision and non-tilting conditions, which are crucial to successful insertion. Although the generalized centroid is similar to the compliance centre of RCC in kinematic property, they differ in essence. [137] developed dynamic equations for chamferless peg-in-hole insertion without the passive compliance in six distinct cases. Exact inequalities for no-wedging and/or no-jamming conditions together with the geometric conditions in two point contact case were established. [138–140] gave an overall dynamic analysis frame of insertion with compliantly supported rigid parts. The model considers various factors influencing the behaviour of dynamic insertion process, and is valid for both chamfered and chamferless insertion. [140] detailed the derivation, and the results were more reasonable.

Figure 4. Dynamic RCC.

The possibility of jamming or wedging arises when friction depends on he magnitude of the contact force. Given the Coulomb model, singularities in the dynamic equations associated with jamming and wedging are due to a breakdown of the rigid-body assumption. [141] provided tests for identifying the onset of jamming and wedging from the dynamic equations. Three common descriptions of the constrained dynamic equations are formulated to include friction, and jamming and wedging conditions for each formulation are presented and proven.

[142] examined the sensitivity to interference between a robot and its environment and established rules for generating optimal assembly trajectories within a predefined force limit. The method considers the complete robot dynamics and can be applied to robots with a conventional position controller, and thus significantly increases the reliability of automated assembly processes. The results of the impact dynamics yield limitations for the maximum assembly speed and also give hints for desirable chamfer design.

For dynamic assembly control, the speed of a software-controlled system is, unfortunately, limited by the control system bandwidth [82]. This motivates the use of passive mechanical device in order to implement force control. The robotics community is recently reassessing the property of passivity in a controlled system and the related advantages, especially in energetic interaction with the environment. Even in the case of active stiffness control, a certain degree of passive compliance is required to prevent jamming. Passive compliance is also necessary to overcome limited position resolution, to enhance disturbance-rejecting capability, and to stabilize force serving loop [143]. Passivity of a system guarantees its stability. Only a passive system remains stable at all frequencies when coupled to an arbitrary passive environment [64]. Experimental results [144] for impact control indicated that for very stiff environments, stable impact control may be achieved only at low velocities. Passive compliance is the only solution consistent with low cost, fast response, high reliability, and low contact forces for high-speed assembly.

A passive mechanical device can regain some of the versatility of its active counterpart if it incorporates passive mechanical elements with programmable parameters, such as tunable damping coefficients or spring stiffness. [145–147] studied passive programmable devices in an attempt to qualify the usefulness of passive device. The authors propose methods choosing damping coefficients to achieve a desired accommodation matrix that is, how to program a mechanical computer. [148] propounded a new frame work with in which the desired end-effector compliance can be specified for stiffness matrix. This realization of variable compliance enables a high stiffness for rapid and precise motion and a low stiffness for force control. Furthermore, the realization of nondiagonal stiffness characteristic, in which force and motion in different directions were coupled, is effective for avoiding jamming and vibration caused by contact. [146] also found that nondiagonal accommodation is useful for the error-corrective assembly. [149–151 implemented impedance-control-based passive assembly. Using a neural network to learn the assembly dynamics, and using a gradient search method with progressive learning strategy, the optimal impedance of robot was learned, and was then used to implement passive assembly. The progressive learning method can minimize the damage to a robot system during on-line learning.

9. Conclusion

Assembly robotics covers a wide range of research topics. Although we have made an effort to provide a general overview, many areas, such as assembly path planning and assembly programming language have still been omitted. We think the following areas serve further study.

1. Mechanical peg-in-hole assembly is a typical production task. To date, the greatest obstacle to robotic assembly is its low productivity. The research on high-speed assembly is crucial to industrial production. This involves study of such areas as dynamic modelling, dynamic conditions for successful assembly, and control and assembly strategies.
2. Micro-assembly and micro- or even nano-manufacturing, such as high-volume microelectronic component assembly, are in rapid development. These produce light-weight and delicate end effector, and micro-robot manipulators are increasingly in demand. This field has become an active one in assembly robotics research.
3. Magnetic levitation wrists with micro and submicron resolution provide an effective means of high-precision assembly, including microelectronic and mechanical assembly. They should be intensively studied and be employed in industrial production.
4. Multifingered hands have been proved to be powerful in assembly use, a very active field. We anticipate that commercially available cost-effective multi-fingered hands together with viable grasping strategies for assembly application will soon appear.
5. Parallel structures for robotics use have been widely acknowledged. Due to their good performance, wrists or robots employing parallel structures greatly improve the performance of assembly tasks.
6. Sensing is indispensable for assembly robotics. To improve assembly performance, we need to strengthen the research on high-quality sensors and advanced signal-processing techniques, and to reinforce the use of multisensor fusion techniques.

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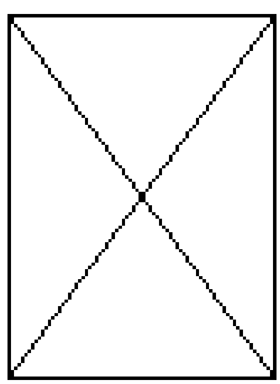
Biographies



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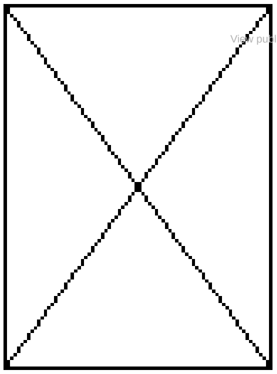

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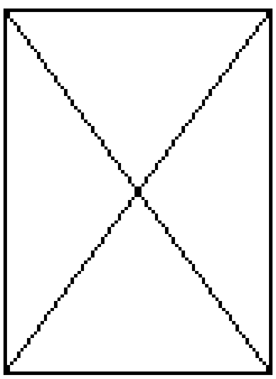

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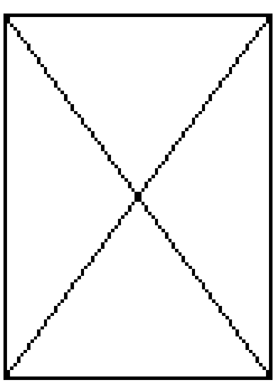

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