A Reconfigurable Fixturing System for Robotic Assembly

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Abstract

Traditionally, fixtures have been required to be redesigned and remanufactured for every new product or manufacturing operation. Although this kind of fixturing practice might be economical for mass production, it would cause long lead times and high (fixture) manufacturing costs in small batch production. In today’s flexible automation approach to small batch production, reconfigurable fixtures can play an important role in addressing these two concerns.

The objective of this research was to develop a reconfigurable fixturing system for robotic assembly. The required features for such a system were in turn set as: modularity, automatic reconfigurability, sensory feedback controllability, and programmability.

The modular fixture component designs which were developed include horizontal and vertical locators, a V-block, horizontal and vertical clamps, and a hole type baseplate on which these components can be reconfigured. All the components incorporate a standard sensing scheme. The main features of the developed fixturing system were verified through the manufacturing and testing of a prototype, which was interfaced to a personal computer.

Keywords: Flexible Manufacturing, Modular Fixtures.

Introduction

Reconfigurable fixtures generally imply that they have been designed for a family of workpiece geometries and/or manufacturing operations. These types of fixtures are most suitable for batch and production and job shop environments where they can be used by many different products. The concept of fixture reconfigurability was developed in the 1960’s for the machine tool manufacturing industry, where such fixtures consisted of kits of standard modular components such as, locators, V-blocks, and clamps assembled on a baseplate. Recent research in this area indicate a new trend toward developing conformable and/or modular fixtures, some of these are presented below to give insight into the state-of-the-art in reconfigurable fixtures.

The modular programmable conformable clamping system developed by M.R. Cutkosky, et al. was designed for fixturing a variety of turbine blade forgings. This system consists of two-section clamps, where the lower half of each clamp employs pneumatic plungers such that, when released, are free to conform to the profile of the turbine blade. The modular fixturing system developed by J.L. Colbert, et al. was primarily designed for the machining of prismatic workpieces. This fixture includes a baseplate, tool points units, and clamps. The baseplate has two sets of hole patterns—one for the mounting of the tool points and clamps, and the other for hydraulic fluid supply to the clamps. The tool point unit is equipped with a microswitch activated by the motion of the tool point when a workpiece is in contact.

The automatically reconfigurable fixture developed by H. Asada and A.B. By was specifically designed for assembly. This modular fixture includes locating pins (locators), guides, and clamps, and can be configured using a robotic device. The main limitation of this fixture is that the baseplate is a magnetic chuck, and therefore, only useful for nonmagnetic workpieces. The automatic modular and adaptable fixture developed by J.H. Buitrago and K. Youcef-Toumi consists of multi-pin modules that can conform to the workpiece geometry. The modules, in turn, consist of three main parts, i.e., array of pins, a shape memory alloy (SMA) actuator, and a modular interface.

Other alternative technologies that have been reported in the literature include the pseudo-
phase-change fixture, the petal collet clamping device, and the multileaf vise. These types of fixtures cannot be considered as true practical fixtures, since they require external augmented systems to define the location and orientation of workpieces during loading/unloading. Although they have higher flexibility in accommodating a large variation in workpiece geometries, most of them cannot provide good rigidity to support the workpieces.

Most fixturing systems presented above had been either developed for a specific purpose or limited in number of applications. They are, also, limited in possessing “intelligence” in the form of sensor integration and programmability. The objective of our research was therefore to develop a reconfigurable (of modular type) fixturing system for assembly operations with the following basic features: modularity, automatic reconfigurability, sensory feedback, and programmability.

**Conceptual Design**

A fixture is a production tool that locates and securely holds a workpiece so that the required manufacturing operations can be performed. Fixtures can be classified as dedicated or reconfigurable. Dedicated fixtures are designed and manufactured for specific products or manufacturing operations. They are usually manufactured by installing (or machining) conventional locators and clamps on either a baseplate or a sidewall depending on the type of operation.

Modular fixtures, the most common reconfigurable fixtures, consist of a variety of standard components such as locators, V-blocks, and clamps, similar to those used for dedicated fixtures assembled (configured) on a baseplate. They are reconfigurable according to product design or manufacturing operation changes, and thus, they are most suitable in batch production and job shop environments.

The reconfigurable fixturing system (hardware and software) presented in this paper is designed and developed for robotic assembly operations, with an assumption that the assembly operations occur along the vertical direction, i.e., layered assembly. The basic design simplification for assembly fixtures, as opposed to machining fixtures, is the lack of consideration for high cutting forces or liquid coolants.

**Reconfigurable Fixture Design Requirements.**

The general design requirements pertinent to dedicated fixtures were adopted for the design of the reconfigurable fixture proposed in this paper, since the objective of the research was to develop a viable alternative to dedicated fixtures. These requirements include positive location, rigidity, ruggedness, repeatability, minimum distortion of workpieces, tolerance to small variations in workpiece geometry, and reliability. The additional design requirements specific to the development of the reconfigurable fixture, on the other hand, include:

1. Modularity: the fixture must be composed of standard modules, which can be assembled on a baseplate.
2. Automatic reconfigurability: the fixture must be reconfigurable by a robot, i.e., the fixture components should be designed for robotic assembly).
3. Sensory feedback controllability: the fixture components must be integrated with sensors for feedback controllability.
4. Programmability: the operation of the fixture must be programmable by a computer.

**Mechanical Design of Fixture Components.**

The first decision to be made in designing the reconfigurable fixture was the interface between the modular components (locators, clamps, etc.) and the baseplate. The two basic types of baseplate geometries considered were the T-slot type and the hole type. The hole type baseplate was chosen due to the following advantages:

1. The assembly of the fixture components on the baseplate is always in the vertical direction, thus, the robot is required to perform only “peg-in-hole” type operations. Whereas, for the T-slot type baseplates, the insertions of components have to be sideways.
2. The sensor integration is easier in a hole type baseplate, since the interfaces can be located at fixed locations directly under the holes. Whereas, for T-slot type baseplates, the locations of components can be continuously varied along the slots, thus, the sensors have to be designed accordingly.
3. The fixture components can be more accurately
assembled on a hole-type baseplate than they would be on a T-slot type baseplate, since the hole locations are known with respect to reference frame with a high degree of accuracy.

The following inventory of components, which can be reconfigured on the hole type baseplate, was envisioned to yield an effective reconfigurable fixture: horizontal locators for external profile support; vertical locators for external support from underneath; V-blocks for external profile support of cylindrical workpieces; horizontal and vertical clamps. The mechanical designs and functional aspects of these components, as well as the baseplate, will be discussed later.

**Sensor Integration.** Sensor integration is vital to the design of a programmable fixture. Sensors allow real-time information transfer between the fixture and its controller. The purpose for sensor integration into the fixture components, within the context of the reconfigurable fixture development, was three-fold, i.e., verification of the proper insertion of the fixture components into the baseplate, detection of the workpiece presence, and control of the clamping process.

In this research, three types of transducers, namely the piezoresistive, the piezoelectric and the electro-optical transducers were considered. The electro-optical transducer was selected to be used in the fixture component designs based on the following pertinent advantages:

1. Freedom from electro-magnetic interference
2. Passive operation (no electronics or power required as the sensing point)
3. Insensitivity to temperature, and
4. Simple electro-optical interfaces.

The electro-optical Y-guide distance sensor was selected to be incorporated into the fixture components as a “proximity sensor.” This design uses two optical fibers positioned across an orthogonal surface, with one end coupled to an emitter, and another to a receiver. The approximate light intensity output of this sensor is shown in Figure 1. However, since the proximity sensor for the reconfigurable fixture is not intended to measure distance, rather to provide a signal to indicate whether an object is in its close vicinity, it has to be implemented in a binary format. To achieve this objective, the analog signal received from the sensor is digitized such that when the reflected light intensity is below a threshold value, an OFF signal is sent to the controller, otherwise, an ON signal is sent. Therefore, as an object approaches the sensor from a distance and touches the sensor, an OFF/ON/OFF signal sequence is received by the controller. The application of this scheme to the reconfigurable fixture is discussed later.

**Computer Interface.** The sensing and clamping operations of the reconfigurable fixture are to be controlled by a personal computer (PC) through a remote interface circuit. In this scheme, the digital command signals are to be sent from the PC to the remote interface for the initiation of the clamping operation for example, through the PC’s parallel port, while analog signals from the sensors are received through an analog to digital board (ADDA card) located in the PC.

Software programs have to be developed for the input/output signal processing and the control of the
fixturing process, namely for component insertion verification, workpiece presence detection, and clamp actuation.

**Mechanical Design**

**Horizontal Locator.** The main components of this locator design include a contact ring, a circular flat elastic (rubber) spring, and a reflector rod (Figure 2). The flat thin rubber spring is used to retain the central position of the reflector rod. The locator is chamfered for ease of insertion, and a slot is incorporated for ease of robotic handling.

The Y-guide sensor is configured such that the optical fibers are housed in the baseplate hole, and the light emitters and receivers are remotely placed outside the baseplate. Prior to the insertion of the locator into the baseplate hole, the receiver receives an OFF signal corresponding to the weak ambient light. As the locator is inserted, the light received increases to an ON level (and stays at that level) due to the light reflected from the bottom surface of the reflector rod inside the locator to indicate that the locator has been inserted correctly. A calibration has to be carried out to determine the threshold level of light reflected by the locator, at which the signal interpreted by the controller is “ON”. When a workpiece is located against the locator, at any orientation, the contact ring displaces the reflector rod sideways, away from its counter position, to cause a drop in reflected light intensity to an OFF level (Figure 3).

The main advantage of this design is that it can be inserted into the baseplate hole at any orientation, due to its axisymmetric nature. Therefore, a locking mechanism for avoiding rotation of the locator in the baseplate hole is not required. However, a locational clearance fit ($H7/h6$), which provides an accurate snug fit, but free assembly has to be employed.

**Vertical Locator.** Two types of variable height vertical locators were designed, namely, a hydraulic locator and a pneumatic locator.
The Hydraulic Vertical Locator. The main components of this vertical locator design include a hollow piston, a core valve, two elastic membranes, a sensing pin, an O-ring, and a light reflector (Figure 4). The core valve is connected to the light reflector which has two slots for the flow of the hydraulic fluid. The O-ring is used for preventing hydraulic fluid leakage. The locator is chamfered for ease of insertion, and a slot is incorporated for ease of robotic handling.

The same sensor configuration used for the horizontal locator is also used for the vertical locator in order to achieve a standard interface mechanism between the modular fixture components and the baseplate. The only difference is that when a workpiece is located on top of the locator, the reflector moves downward (due to the incompressibility feature of the hydraulic fluid), instead of deflecting sideways to cause a drop in reflected light intensity (Figure 5).

Care must be exercised in preventing the entrance of air into the locator during the height setting process. In the case of air in the locator, it is possible that when the sensing pin is pressed downward, the air would be compressed, and thus the reflector would not be displaced the required distance to block the light.

The vertical locator must be filled with the hydraulic fluid during its manufacturing process. The height of this locator must therefore be set with an external device prior to its insertion into a
baseplate hole where the extra fluid is either injected into the locator to increase the height, or removed from it to decrease the height. This height adjustment process, as illustrated in Figure 6, is as follows:

1. The locator is inserted into the height setting mechanism base.
2. The core valve is pressed from underneath and hydraulic fluid is injected into the locator to cause the hollow piston to move upward. At this stage, the core valve and the reflector are at higher positions and the bottom membrane is stretched.
3. The piston extends until it touches the external height setting device.
4. Then the core valve moves to its lower limiting position due to the hydraulic pressure inside the locator.
5. Once the valve is shut, the external height setting device is removed, and the height of the locator is locked in that specific configuration due to the incompressibility feature of hydraulic fluids.
6. Lastly, the spring pushes the sensing pin upward. Although the upper membrane can also provide an upward force, it may not be strong enough, thus a spring was included in the design for reliability. The core valve and the reflector also move upward, once again, due to the incompressibility of the fluid.

**Pneumatic Vertical Locator.** The main disadvantage of the hydraulic vertical locator design is the possible leakage problem of the hydraulic fluid. Thus, a pneumatic type variable height vertical locator was designed. The main components of this vertical locator design include a piston, an O-ring, eight ball bearings, a steel ring, a sensing pin, a collet, a collet closer, and a reflector (Figure 7). In this design, a mechanical locking mechanism is employed to maintain the set height, as opposed to hydraulic fluid.

The locator insertion verification is the same as the previous locator designs. The reflected light intensity increases from an OFF level to an ON level as the locator is successfully inserted. Similar to the hydraulic vertical locator design, when a workpiece is placed on top of this locator, the sensing pin and the reflector move downward to block the light to indicate workpiece presence (Figure 8).

Initially, the sensing pin is clamped by the collet, which is connected to the reflector located at the bottom. The piston is locked in its position by the ball bearing wedge type self-locking mechanism. As the ball bearings drop to the lower position in between the wedge surface and the piston, they cannot move upward without applying an external force (self-locking). Therefore, the piston is also locked by the friction that occurs on the piston and the wedge surfaces.

The height of this locator also has to be set with an external device prior to its insertion into a baseplate hole. The height adjustment process, as illustrated in Figure 9, is as follows:

1. The locator is inserted into the height setting mechanism baseplate.
2. Air is injected into the locator to release the lock that holds the piston by pushing the ring upward, which then in turn displaces the ballbearings upward. This yields a small gap between the ball bearings and the piston so that the piston can move freely.
3. The air pressure causes the piston, together with the collet, to move upward, and the collet closer to move downward. This bi-directional motion compresses the collet spring to open the collet.
4. As the piston continues to move upward, the light reflector moves downward until the piston is constrained by the external height setting device and the reflector constrained by the base.
5. The supply of air is then halted. The ring first moves downward, then the ball bearings follow due to gravity and the spring force exerted by the O-ring. Since the piston may also drop before it is locked, and thus cause inaccuracy in height, the O-ring is utilized to provide a frictional force to hold the piston in place and prevent it from moving downward before it is locked. The O-ring also provides sealing function.
6. Once the piston is locked, the collet is closed by the force exerted by the collet spring to rigidly clamp the sensing pin.
7. Lastly, the height setting mechanism can be removed to release the sensing pin and the reflector which are held together.

Compared to the hydraulic type locator, this pneumatic locator is easier to maintain, however, it is a more complex design.

**V-block.** The main components of this V-block design include a V-shaped reflector, a spring, and a teeth-incorporated base (Figure 10).
Figure 6
Hydraulic Vertical Locator Height Setting Procedure
is chamfered for ease of insertion. The location of the V-block on the baseplate, unlike the locators’, is “directional”, (i.e., its orientation must be predetermined). Therefore, a teeth-incorporated electromagnet locking mechanism was designed to prevent the V-block from rotating during the fixturing process once it is inserted into the baseplate.

The locking mechanism consists of a coil and teeth-incorporated ferro-magnetic insert in the baseplate hole, onto which the corresponding teeth-incorporated base of the V-block meshes. When the V-block is inserted into the baseplate hole at the correct orientation, the coil is powered to generate the necessary magnetic field to hold the V-block in place. The teeth ensure that the V-block does not rotate about its vertical axis during the fixturing process. The magnetic field does not affect the fixturing of ferro-magnetic workpieces, since the ferro-magnetic base is isolated to the bottom part of the V-block.

The sensing scheme is the same as that for the vertical locators, with the exception of the V-shaped reflector instead of the pin-type reflector. When a cylindrical workpiece is placed on the V-block, the spring loaded reflector moves downward to block the reflected light (Figure 11).

Horizontal Clamp. The main components of this horizontal clamp design include a pneumatic cylinder, a cylinder wedge cover, a sensing pin, a spring, a teeth-incorporated base, and an exchangeable-
Pneumatic Vertical Locator in Contact With a Workpiece

clamp head (Figure 12). The location of the horizontal clamp on the baseplate is “directional” as the V-block. Therefore, the locking mechanism used for the V-block was adopted for the horizontal clamp as well.

The sensing scheme is the same as for the other components already presented in this section. The operation of the clamp, as illustrated in Figure 13, is as follows:
1. When the clamp is actuated, the cylinder rod extends until it is in contact with the workpiece.
2. At contact, the reaction force from the workpiece causes the cylinder and its wedge cover to move backward.
3. During the reverse motion, the wedge cover pushes the sensing pin downward to block the light reflected into the receiving optical fiber in the baseplate hole.

Vertical Clamp. The main components of this vertical clamp design include a two degree of freedom (dof) mechanism, which consists of two revolute joints, a pneumatic cylinder, a locking mechanism, and a sensor line (Figure 14). The two dof mechanism, similar to a SCARA type robot, was designed so that workpieces can be clamped within a large workspace. The revolute joints consist of precision shafts with O-rings for providing sufficient friction to prevent rotations once the required clamp configuration is set.

A locking mechanism that uses belleville springs was designed to withstand the vertical reaction forces. As shown in Figure 14, the clamp can be inserted into a baseplate hole at two symmetrical orientations. The clamp is pressed into the hole against the belleville springs and rotated by 90 degrees (clockwise) until it touches the mechanical stops. Once this is accomplished, the belleville springs would force the clamp to rise and lock it in place. A reverse course of action is necessary in order to release the lock and remove the clamp.

The sensing scheme is similar to the one for the horizontal clamp with the exception of the additional sensor line, which has a flexible wire inside: a tube that is attached to the sensing pin. The sensing operation, as illustrated in Figure 15, is as follows:
1. Air is supplied to actuate the clamp.
2. When the clamp is in contact with the workpiece, the reaction force from the workpiece causes the cylinder to move backward, and thus, displaces the sensing pin.
3. The flexible wire inside the sensor line moves along its cover, and thus, its other end blocks the light reflected into the receiving fiber in the baseplate.

The disadvantage of this clamp design is that a different type of baseplate hole is required. Therefore, the clamp can only be placed at specific locations.

Baseplate. Based on the fixturing component designs described in this section, a specific baseplate, which consists of two types of holes, was designed:
1. Those that contain the ferro-magnetic inserts for all locators, V-blocks, and horizontal clamps,
Figure 9
Pneumatic Vertical Locator Height Setting Procedure
Figure 16a, and
2. Those that contain the belleville spring housings for vertical clamps (Figure 16b).

Two optical fibers are located in the centers of both the ferro-magnetic inserts and the belleville spring housings.

A matrix of holes for the electro-magnetic locking mechanisms are located in the inner part of the baseplate, while two (perpendicular) rows of holes...
Figure 12
Horizontal Clamp

Figure 13
Horizontal Clamp in Contact With a Workpiece
for the belleville spring locking mechanisms are located along the two baseplate edges, to allow the vertical clamp to reach any point on the baseplate.

A Prototype Reconfigurable Fixture

A set of fixture components were selected for verifying the concepts developed, especially the sensing scheme, and the electro-magnetic locking mechanism. The prototype reconfigurable fixture consists of a baseplate, a sensor integrated "intelligent" horizontal locator, a "dummy" locator, and a horizontal clamp, (Figures 17-20). The "dummy" locator is geometrically equivalent to the "intelligent" locator without the sensing capability.

An IBM PC-AT was used as the fixture controller. The interface diagram is shown in Figure 21. The software, designed for experimentation with this prototype consisted of three subroutines aimed at:

1. Locator/clamp insertion verification
2. Workpiece presence detection, and

This prototype reconfigurable fixture, even with its limited number of components, could be used to accommodate workpieces of different sizes and shapes (Figure 22). The sensing scheme, the teeth-incorporated electro-magnet locking mechanism, the interface circuit, and the control software were successfully tested by the fixturing processes of these example workpieces.

Concluding Remarks

Most of the existing fixtures for flexible automation reported in the literature, have been designed for specific types (geometries) of products, and with very limited sensing capabilities (or not at all). The objective of this research was therefore set as to develop a reconfigurable fixturing system for robotic assembly. The required features for such a system were in turn set as: modularity, automatic reconfigurability, sensory feedback controllability.
and programmability.

The reconfigurable fixture inventory includes all-sensor-integrated, horizontal and vertical locators, V-block, horizontal and vertical clamps, and a hole type baseplate. The modularity of the fixture is achieved through the baseplate design, which allows reconfigurability of the fixture components.
Figure 18
Horizontal Locator

Figure 19
Horizontal Clamp

Figure 20
Baseplate

Figure 21
Interfacing Scheme

Figure 22
Fixturing Examples
for the workpiece geometry at hand.

The sensing scheme is based on the use of the Y-guide proximity sensor where the optical fibers are housed in the baseplate holes, and the light emitter and receivers are remotely located. A reflector (which either moves in the vertical direction or deflects sideways to change the reflected light intensity), as a workpiece is in contact with the fixturing component, is included in every component. This scheme offers advantages of remotely located electronics for the sensors and easy maintenance.

The manufactured reconfigurable fixture prototype of selected components was successfully tested to verify the sensing scheme, the electro-magnetic locking mechanism, and the interfacing and programming schemes.

The following issues are currently under investigation: improvement of the mechanical component designs to increase flexibility, optimal reconfiguration of the fixture based on CAD models of the objects and the fixture components, and integration of the reconfigurable fixture into a robotic workcell.

References

Author(s) Biography
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