

Kinematic Couplings for Pallets in Flexible Assembly Systems

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Abstract

Flexible assembly systems use conveyors to transfer products through a series of workstations. The product being assembled is typically held in a fixture mounted on top of a pallet. Conventional approaches for locating the pallets often use precision ground pins and bushings for location. This technique requires clearance between the pin and bushings to accommodate manufacturing variation and prevent binding. For one system, this clearance limits the repeatability of the pallet to 100 microns. For high-precision assembly operations, the non-repeatability of the pallet can be one of the largest sources of variation and lead to low quality or poor yields. This paper presents kinematic couplings as an exact constraint approach for locating pallets in flexible assembly systems. The paper describes a split-groove kinematic pallet used in a flexible assembly system for electrical connectors. The repeatability of the kinematic pallet was measured in factory-like conditions. The repeatability was within 10 microns, which is about an order of magnitude improvement over a leading industrial pallet.

Keywords: kinematic couplings, pallets, flexible assembly systems, and assembly automation

Introduction

During the 1970s and 1980s, flexible assembly systems were developed as an alternative to hard automation that used fixed tooling and machinery. Flexible assembly systems offer the ability to produce a variety of products within the same production system, achieving small batch sizes (sometimes as low as one unit per batch). Flexible assembly systems collect independent workstations into an integrated system connected by a material handling system that transported pallets between workstations. Each pallet carries a fixture capable of holding one or more product assemblies. Powered conveyors with sensors and logical controls are frequently used as the material handling system. In the 1980s, several suppliers of assembly automation released product lines for constructing conveyor systems from modular components [1], and systems using these components are now standard practice within industry.

While designing a flexible assembly system for electrical connectors [2], the variation in pallet location was the largest source of error in the error budget [3]. This amount of variation prevented the connector from being reliably assembled at reasonable quality levels. Therefore, a new approach

was developed that used kinematic couplings between the pallets and workstations. Kinematic couplings (and Kelvin clamps) are well-known deterministic mechanical solutions for precisely locating one object with respect to another [4],[5].

This paper presents kinematic couplings as a new alternative for precisely locating palletized fixtures on workstations in flexible assembly systems. The paper begins with a description of an industrial pallet system and the pallet's locating method. Then, the design of a split-groove kinematic pallet is presented. Repeatability measurements of the split-groove kinematic pallet are presented, and the kinematic pallet is shown to be repeatable within ± 0.005 mm (± 0.0002 in), an order of magnitude improvement over the conventional pallet.

Conventional Pallet Designs

In one style of modular conveyor systems [6], the pallet is constructed from a molded polyimide frame, a steel or aluminum plate, and four hardened steel bushings. The plastic frame encloses the perimeter of the plate, and the entire assembly is joined by pressing the bushings into the frame and plate. These same bushings are used with ground

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pins to locate the pallet at workstations. The precision ground pins, mounted on the workstation, slide into the bushings within the pallet. The precision ground pins are available in two varieties, one variety with a round profile and one with a diamond profile.

The locating method for this style of pallet is illustrated in Fig 1. The method usually uses one of the round pins and one of the pins with flats. The round pin constrains the translational degrees of freedom (in the plane), and the pin with flats constrains the rotational degree of freedom. With this approach to locating the pallet at the workstation, the clearance between the bushings and pins limits the repeatability. The clearance is necessary to accommodate manufacturing variation in the location of the bushings and the distance between the holes. The clearances limit the pallet repeatability to about ± 0.05 mm (± 0.002 inches) in the plane [6].

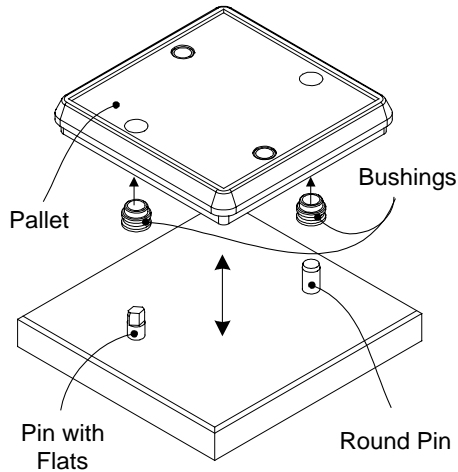


Fig 1: Position method for conventional pallets

Split-Groove Kinematic Pallet Design

Kinematic couplings are exact constraint [7] devices for positioning one body with respect to another body. Kinematic couplings come in many forms, but the two most common configurations are the Kelvin coupling and the three-groove coupling [8]. Kinematic couplings connect two bodies through six contact points, exactly enough for static equilibrium. This ensures that the coupled body is statically determinate.

Kinematic couplings derive three advantages by ensuring that the body is statically determinate. First, no strain is induced in the coupled body due to forced congruence between the coupled bodies. The second advantage is that a single preferred relative position

between the two bodies exists (due to minimizing potential energy). The third advantage is that the coupling is deterministic, which means that its performance is predictable. Unfortunately, kinematic couplings also have some limitations. Since the contact between the bodies is limited to six points, the reactions at the contact points are distributed over very small areas. This Hertzian contact produces large stresses at the contact points. The deformation at the contact points that arises from the contact stress also limits the static stiffness between the coupled bodies.

For the kinematic pallets, an adaptable variant of the three-groove kinematic coupling was used. This variant, called a split-groove kinematic coupling, splits one of the grooves to provide a wide baseline to enhance packaging in space-limited systems. A split-groove kinematic coupling is illustrated in Fig 2. The six contact points exist between the flats of the vee-grooves and the balls. Vallance provides a technique for designing split-groove couplings and considering their stability to disturbance forces [2].

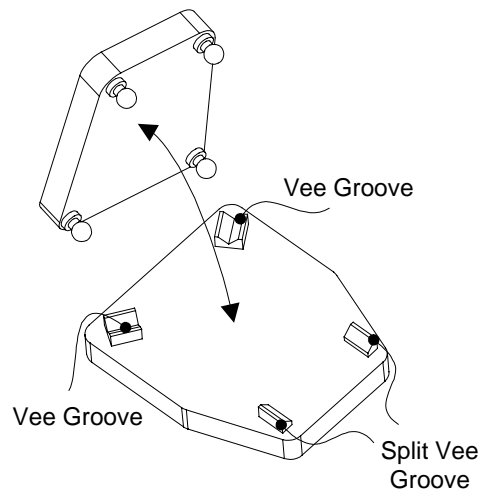


Fig 2: Split-groove kinematic coupling

The split-groove kinematic coupling was designed into a conventional assembly pallet by incorporating the balls into the fixture plate, which fastens onto the top of the conventional pallet. The vee-grooves were designed into the assembly workstation. The split-groove allowed the vee-grooves to straddle the width of the conveyor system and prevented the necessity for locating a vee-groove in the center of the conveyor system. The pallet was preloaded into the vee grooves using a set of permanent magnets. The magnetic preload was sized so that adequate stability existed for a range of

disturbance forces, but the preload was not excessive for manually lifting the pallet off of the workstation.

Fig 3 shows photographs of the split-groove kinematic pallet system designed for the connector flexible assembly system [2]. The vee-grooves and the permanent magnets in the assembly workstation can be seen in Fig 3 (a), and Fig 3 (b) shows the pallet coupled to the assembly workstation.

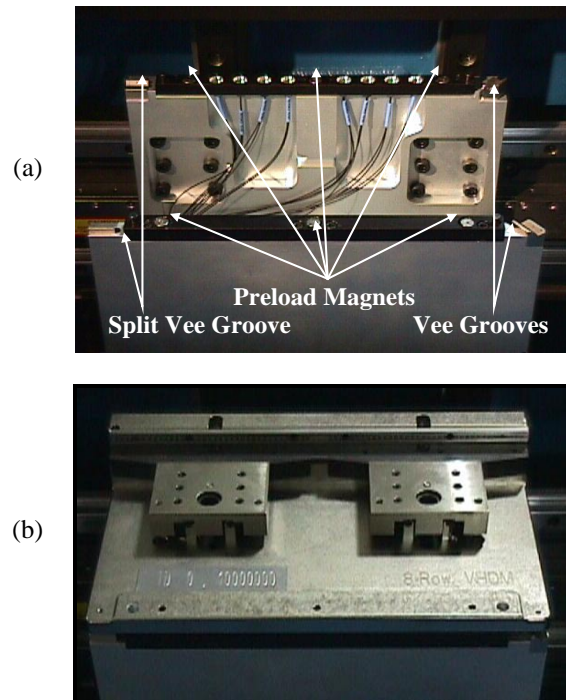


Fig 3: Split-groove kinematic coupling in assembly workstation

Pallet Repeatability Measurements

The repeatability of the split-groove kinematic pallet was assessed experimentally. The experiments were conducted on an instrumentation fixture, shown in Fig 4, which duplicated the geometry of the assembly workstation, including the split vee-groove, the conventional vee-grooves, and the preload magnets. The pallet was lifted and dropped onto the grooves by a pneumatically actuated plate. The lift plate was guided by die set bushings, and it separated from the pallet at the bottom of travel to prevent over constraining the pallet. Capacitive distance sensors were mounted around the pallet to measure the variation in the location of the pallet. Each sensor provided an analog signal (± 10 V) proportional to the change in the distance between the face of the sensor and a steel target attached to the pallet (± 50 μm). A 16-bit data acquisition system was configured to measure signals between ± 5 V, providing a resolution around 0.76 nm/bit.

In factory-like conditions, the pallet was lifted and dropped thousands of times over two days, and the gap distance was measured each time. Fig 5 shows a plot of the four sensors' measurements in microns. The expansion and contraction of the pallet and fixture due to ambient temperature cycles produced a cyclic error with a period of 24 hours and maximum amplitude of 10 μm in Sensor 1. Additional variation due to the air compressor and pneumatic system produced a periodic trend with a period of approximately 2 hours. Even with the errors produced by the thermal and pneumatic cycles, the pallet was repeatable to within 10 μm . This represents a 10X improvement over conventional pallet location methods, which are only repeatable to about ± 50 μm .

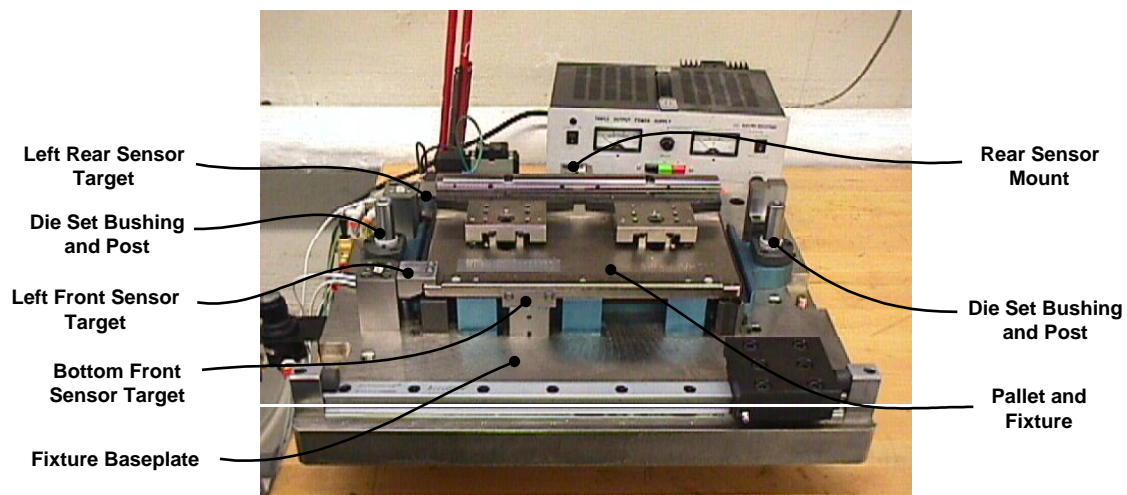


Fig 4: Experimental fixture for measuring pallet repeatability

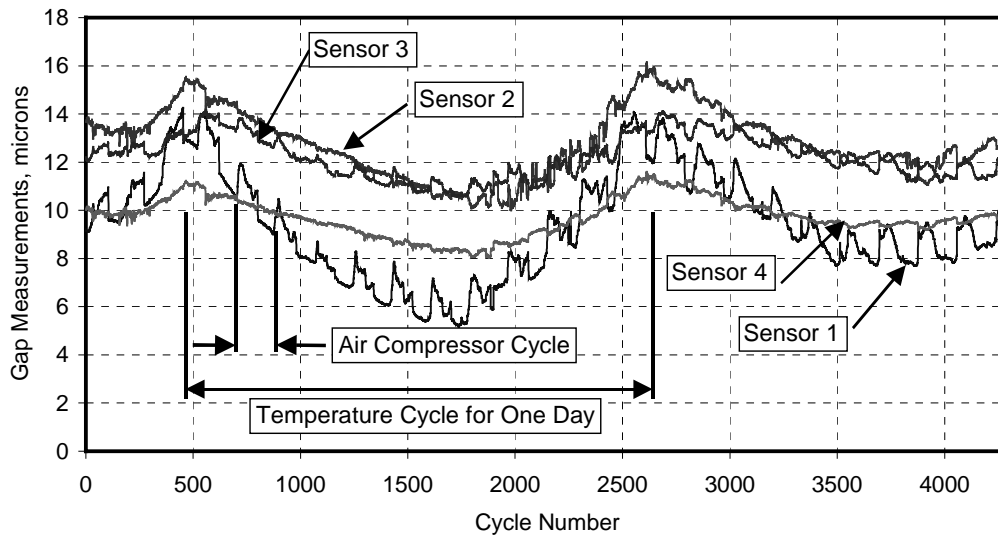


Fig 5: Repeatability measurements for split-groove kinematic pallet

Conclusions and Future Work

Kinematic couplings are an effective approach for improving the repeatability of pallets in flexible assembly systems. At least an order-of-magnitude improvement can be obtained by using a kinematic coupling rather than the standard approach of pins and bushings. A particular embodiment was described that used a split-groove kinematic coupling incorporated into the fixture that mounts on a conventional industry pallet. The repeatability of the kinematic pallet was about $\pm 5 \mu\text{m}$, including variation resulting from thermal expansion and pneumatic cycles. This improvement enables flexible assembly systems to be used for products with stringent precision requirements.

Although the benefits of kinematic pallets were demonstrated in this work, future work is needed to incorporate kinematic features into industry standard pallets. This would prevent having to incorporate the kinematic features into the fixture rather than in the conventional pallet. This will require collaboration with an industry partner that designs and manufactures modular conveyor systems.

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