

A CAD Tool that Automatically Designs Fixtures and Pallets

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NOV 17 1995

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Costs associated with designing and fabricating fixtures may be a significant portion of the total costs associated with a manufacturing task. The software tool, HOLDFAST, designs optimal fixtures that hold a single workpiece, are easily fabricated, provide rigid constraint and deterministic location of the workpiece, are robust to workpiece shape variations, obey all associated task constraints, and are easy to load and unload.

We illustrate the capabilities of HOLDFAST by designing fixtures for several examples. Fixtures are designed and built for finish-machining and drilling of a cast part for prototype fabrication and mass-production fabrication. A pallet fixture is designed for vertical assembly of a personal cassette player. Another pallet fixture is designed and built that will hold either the personal cassette player or a glue gun during assembly.

1 Introduction

Fixtures are commonly used in manufacturing tasks to hold the workpiece during machining, assembly and inspection tasks. A good fixture must meet many requirements simultaneously. The fixture must hold the workpiece securely and in a repeatable location while not interfering with the manufacturing tasks. Variations in workpiece shape and fixture wear must not compromise workpiece holding and positioning. Loading and unloading the workpiece in the fixture must be relatively easy.

The fixture must also be economical. The considerations defining fixture cost-effectiveness vary with the surrounding business enterprise. During the design and development of a product or the production of small lots, the time and expense associated with designing and fabricating good fixtures may be important. If production lots are larger, then reliability, positioning accuracy, and ease of loading and unloading become more important.

The software tool, HOLDFAST, designs optimal fixtures that are easily fabricated. Fixtures designed with HOLDFAST rigidly constrain and locate the workpiece, allow successful completion of the manufacturing task, are easy to load, and are economical to produce.

HOLDFAST fixture designs may be grouped into two broad categories. The first category requires the workpiece to be completely constrained both horizontally

and vertically. An example application for fixtures of this category is finish-machining. The second category of fixtures provide vertical support of the workpiece from below only; these are referred to as pallets in this paper. An example application for this category of fixtures is an assembly operation where the top of the workpiece must remain completely clear.

All fixtures designed by HOLDFAST use a few basic components. The fixturing components are attached to a flat base plate. Cylindrical lateral-locators and a side clamp are used to constrain the workpiece motion in a plane parallel to the base plate. Cylindrical support pads with flat or self-aligning tops raise the workpiece off of the base plate. If it is necessary to completely constrain the workpiece vertically, swing-arm top-clamps are used to hold the workpiece against the support pads.

HOLDFAST designs fixtures that hold the workpiece in kinematic form closure; that is, workpiece motion is possible only if either the workpiece or the fixture deforms. (Pallets are a special case; they resist all movement except vertical movement associated with loading and unloading.) Thus, HOLDFAST fixtures do not rely on friction to prevent workpiece motion. Kinematic form closure orients the workpiece in the fixture; if the workpiece is in contact with all the locators it is in a known, repeatable position. All HOLDFAST fixture designs provide form closure in a plane parallel to the base plate using round lateral locators and side clamp. Support pads and top clamps are used to prevent motion out of the base-plate plane. HOLDFAST places top clamps directly above support points to minimize clamp-induced workpiece deformations.

Holding a workpiece using form-closure places general requirements on the workpiece and the task constraints. Certain types of workpieces cannot be fixtured using form-closure; these exceptions are usually obvious after inspection. Rotationally symmetric objects such as spheres and cylinders are a general class that cannot be fixtured using form closure [Mishra *et al.* 1987]. A clam-shell shaped workpiece that has no parallel, flat surfaces cannot be held reliably by support pads and top clamps. If a rectangular workpiece cannot be contacted along one entire side as a result of manufacturing constraints (such as machining the side surface) then the workpiece cannot be held in form closure by the lateral locators.

*Supported by US DOE contract DE-AC04-94AL85000.

The HOLDFAST algorithm enumerates all possible fixtures considering the workpiece shape, the task constraints, and the fixture kit. Thus, it is guaranteed to find a fixture design if one exists and it is also guaranteed to find the optimal fixture.

Each fixture is scored using quality functions based upon the manufacturing task requirements. Quality functions that are currently in use consider the forces generated at the fixture contacts, the variability in position of workpiece features (resulting from variability in workpiece shape and fixture component location and shape), and whether or not the fixture is easy to load. Other arbitrary quality functions may be defined by the user. Threshold values may be applied to the quality criteria, allowing poor fixtures to be discarded. Upon completion, HOLDFAST displays all fixture designs that pass the specified threshold values.

An interactive interface allows the user to study fixture designs as they are generated. This allows the user to inspect early designs to verify that the inputs are correct and the fixture designs are reasonable. The user may let the program run to completion to find the globally optimal fixture, or stop prior to completion and use a high-quality fixture that appears early.

2 Examples

The capabilities of HOLDFAST can be demonstrated by means of the following examples. The first example designs two different fixtures for completely constraining a workpiece during final-machining and drilling operations. The first of these two fixtures is applicable for prototyping while the second fixture is applicable for mass production of the workpiece. The second example designs pallets suitable for assembly operations. The first pallet is designed to hold a single workpiece. A second pallet is designed that will hold two different workpieces using only a few more fixture elements than a pallet for one individual part.

2.1 Prototype production

During the design and development of a product, typically a small number of copies of the part are fabricated for evaluation. Because of the small production quantities, fixture design, fabrication, and storage costs may be significant for producing the prototype parts. These costs may be reduced by constructing the fixture from re-usable modular elements.

Near-net-shape fabrication methods, such as casting and welding, are efficient for producing parts with complex shapes. However, the lack of precision of these processes requires final machining operations to create precise part features such as gasket surfaces and threaded holes. Figure 1 shows a part that is manufactured by casting a near-net-shape workpiece, and then applying finish machining operations including drilling several holes and milling two gasket surfaces. In the following paragraphs, we show how HOLDFAST may

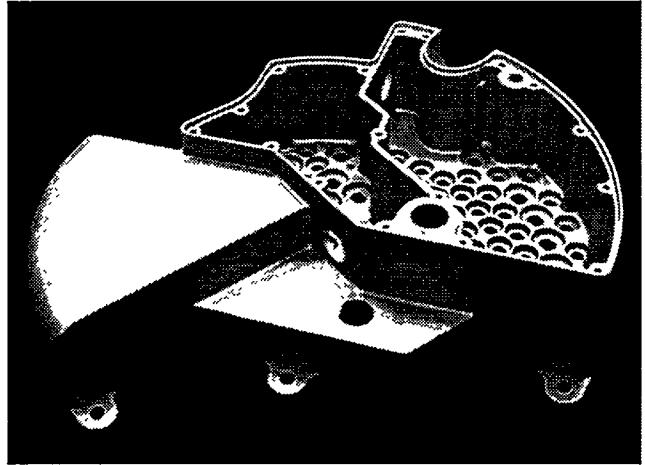


Figure 1: A cast housing that requires finish machining.

be used to design fixtures for both the prototype and mass production of this part.

HOLDFAST input includes information concerning the workpiece, the fabrication process, the fixture kit, clearances, the quality functions used to score the fixtures, and HOLDFAST control parameters. Workpiece information includes a CAD description of the workpiece, constraint regions, and shape tolerances. Fabrication process information may include a description of the machining operations to be performed, expressed as geometric volumes swept by the cutter and a set of forces expected during cutting. A fixture kit is defined by the list of modular elements that may be used, along with each element's nominal shape, tolerance in shape, and tolerance in the mounted position. The quality function used to score the fixtures may specify maximum forces allowed at fixture contacts and the maximum allowable positional error of specified features resulting from variability in the workpiece and fixture. HOLDFAST control parameters may be used, for example, to sample some or all of the space of possible fixture designs.

Using this information, HOLDFAST generates all feasible fixture designs. Each fixture design holds the workpiece in form closure, does not interfere with the fabrication process, and may be assembled using the available fixture elements.

Each fixture is also checked for ease of loading. In this case, a fixture is considered easy to load if (1) the workpiece may be placed in a "loading" position near the loaded position that avoids all the fixture elements by at least a specified clearance, (2) the center of mass of the workpiece in both positions is contained in the triangle formed by the support pads, and (3) there is a placement of the top clamp swing-arms that allows the workpiece to be lowered vertically into the fixture and clamped into the loaded position without a collision. When these conditions are satisfied it is easy for the user to lower the workpiece into place, slide

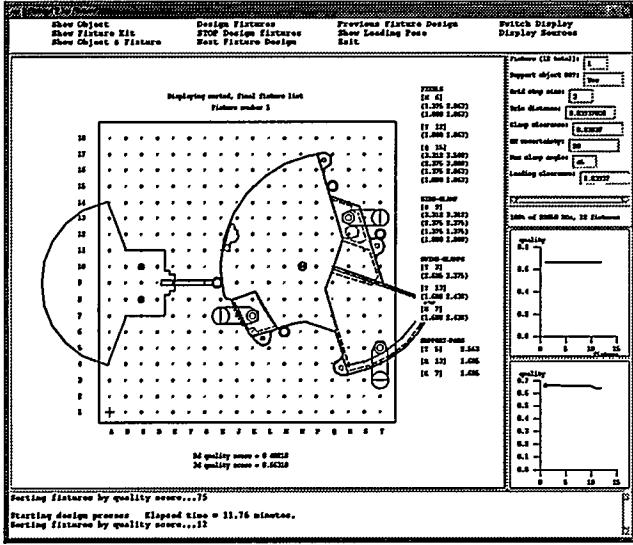


Figure 2: High quality fixture design for prototype fabrication of a cast housing.

it into contact with the lateral locators, and close the clamps one at a time. HOLDFAST generates all fixture designs, but those designs that can be easily loaded have additional information indicating where to place the workpiece and swing arms during loading.

Finally, each fixture is scored according to a quality metric. The quality metric considers the contact reaction forces required to resist the expected machining forces, the required location precision of critical workpiece features, and whether or not the fixture is easy to load. The user can assign thresholds to each of these criteria, and also specify the way the criteria should be combined to produce the overall quality score. Upon completion, HOLDFAST displays a ranked list of all the fixture designs that passed the specified thresholds.

HOLDFAST's interactive interface allows the user to study the fixture designs as they are generated. The interface also displays a plot which shows how each fixture's quality score relates to others that have been previously generated. The user may stop HOLDFAST to utilize a high-quality fixture that appears early in the computation or let HOLDFAST run to completion to find the globally optimal fixture.

For our prototype fabrication example, HOLDFAST output the first fixture design after 35 seconds of computation time. Improved fixture designs began to appear a few seconds later. Figure 2 shows one of these fixture designs which was used to build the fixtures shown in Figures 3 and 4. Physical testing of this fixture indicated that it held the workpiece in form closure and was easy to load.

2.2 Mass production

Prototype production is characterized by small production lot sizes and labor-intensive manufacturing meth-

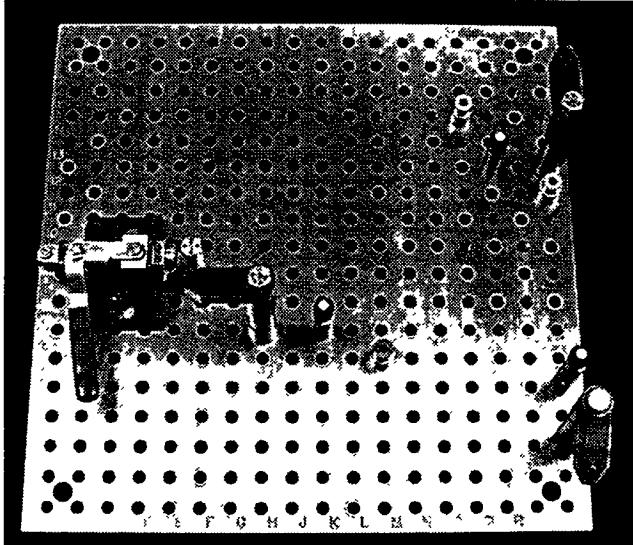


Figure 3: Prototype-fabrication fixture.

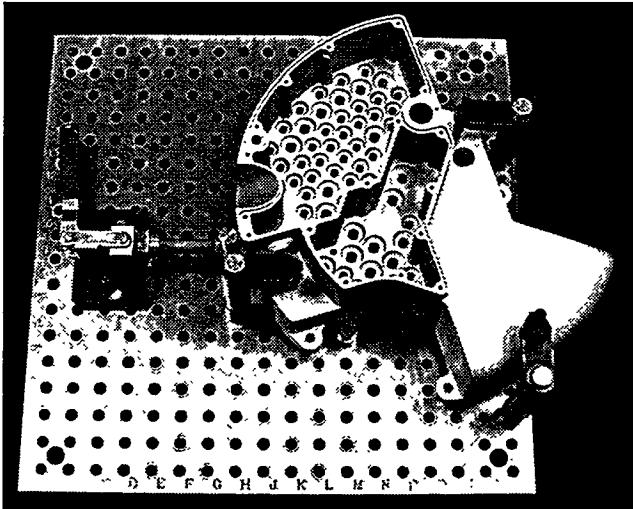


Figure 4: Cast housing in prototype-fabrication fixture.

ods. Mass production of the part shown in Figure 1 is likely to use automated casting and machining methods to reduce production costs.

HOLDFAST may also be used to address this problem. In this scenario, a manufacturing engineer would provide a similar problem definition to HOLDFAST; minor changes in input will produce solutions suitable for automation rather than manual use. The differences between the manual scenario and the automated scenario are discussed below.

1. The manually-actuated clamps are replaced with automated hydraulic clamps.
2. Vertical loadability is strictly required, instead of optional as in the manual case.
3. A more complete search is made to identify and

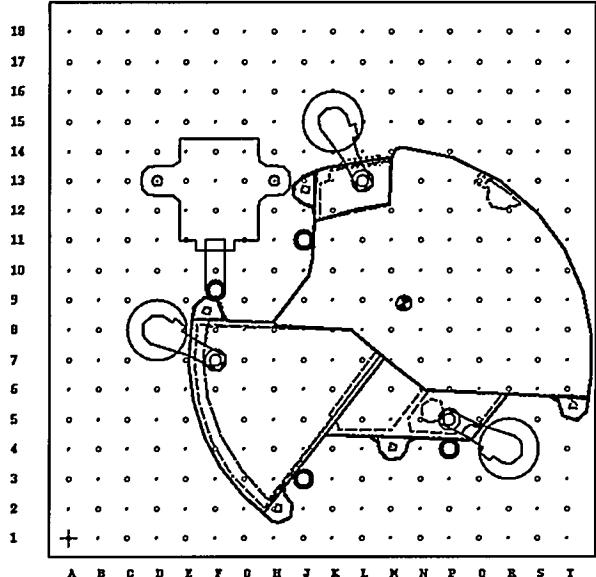


Figure 5: Optimal fixture design for the mass-production fabrication of a cast housing.

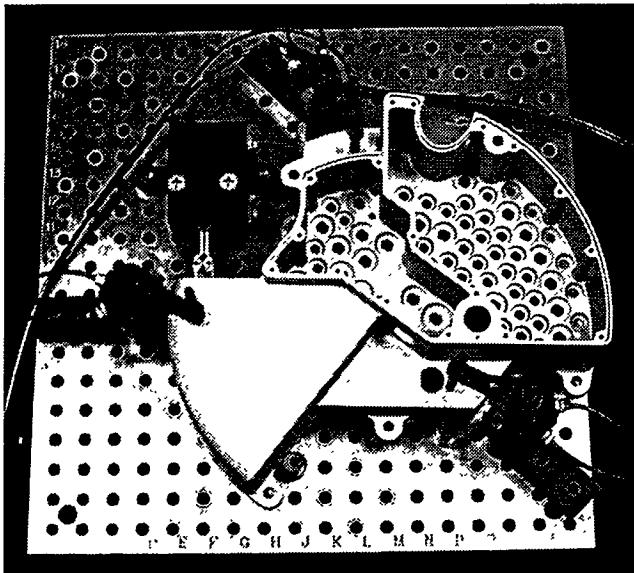


Figure 6: Cast housing in a optimal mass-production fabrication fixture.

evaluate all feasible fixture designs, because the resulting improvements in fixture quality are worth the additional computation time.

4. To reduce fixture fabrication costs, the fixture may be constructed using a plain tooling plate rather than a modular base plate.

Figure 5 shows the optimal solution for the automated fixture design problem. This analysis was performed in 133 minutes of computation time, during

which HOLDFAST considered thousands of candidate designs. Figure 6 shows the part mounted in the fixture. The reliability of loading and unloading the workpiece in the fixture was tested by repeated loading-unloading trials.

2.3 Light Mechanical Assembly

Another manufacturing process that commonly requires fixtures is light mechanical assembly. Products of this type are often designed so that most parts are inserted vertically. For these tasks, it is also desirable to load and unload the assembly from the fixture by vertical motions. These assembly fixtures — often called pallets — must be inexpensive to produce because many copies are required.

Very simple pallet designs consisting of a collection of pins attached to a base plate meet the requirements of vertical loading and unloading of the part and low pallet fabrication cost. The pins have either flat or conical tips. The pins with flat tips support the base part, while the pins with conical tips provide lateral constraint and guide the base part into place during vertical loading. Each pallet has four lateral constraint pins and three or more support pins.

HOLDFAST may be used to design these pallets. Input required by HOLDFAST includes a CAD description of the base part, along with volumes swept by parts and tooling during the insertion operations, a description of the forces that will be exerted during insertion and fastening operations, and tolerances on the location of features critical to the assembly. HOLDFAST then generates all feasible pallet designs that do not interfere with the volumes swept during insertion operations while holding the base part in planar form closure and providing optimal support. HOLDFAST does not perform a loadability analysis; we assume that the conical tips on the locating pins and suitable manipulator compliance will allow successful vertical loading.

These pallet designs are returned in ranked order, based on a quality metric that considers (1) lateral contact forces that occur in response to fastening torques during product assembly and inertial loads during pallet transfer operations, (2) tipping moments induced by vertical insertion forces, and (3) the position variation of critical part features. The user may specify thresholds and combination methods for these three criteria.

Figure 7 shows an example base part and assembly produced in mass quantities; they are parts of a personal cassette player. A number of wheels, gears, and control linkages are attached to the chassis by vertical insertion. The underside of the chassis has several fragile pins extending downward, requiring the assembly pallet to hold the chassis off the pallet surface. A number of the attached parts extend past the boundary of the chassis, which greatly reduces the surfaces available for lateral location.

The optimal pallet is shown in Figure 8. The total

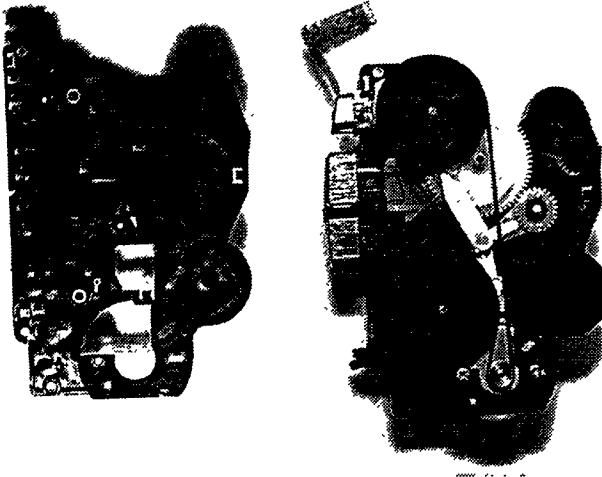


Figure 7: Personal cassette player chassis and assembly.

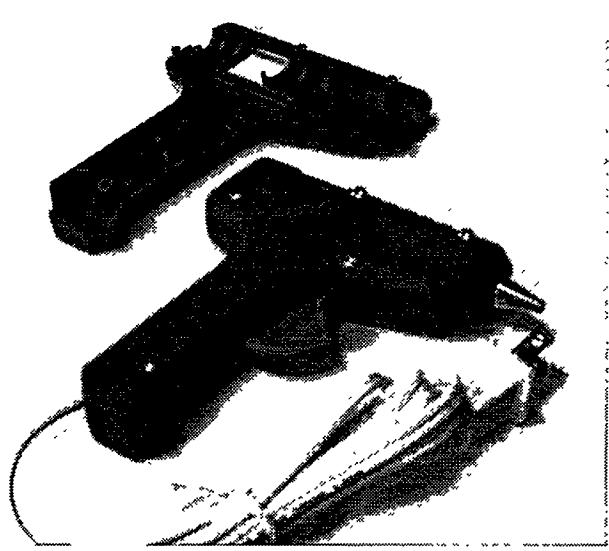


Figure 9: Glue gun housing and assembled glue gun.

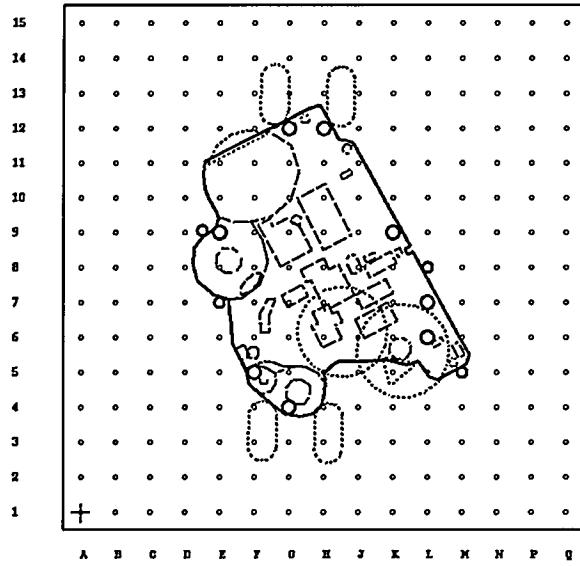


Figure 8: Optimal pallet design for the assembly of a personal cassette player.

design computation took 34 minutes and produced 223 fixture designs. Early designs appeared in about 50 seconds.

2.4 Mixed-Part Light Mechanical Assembly

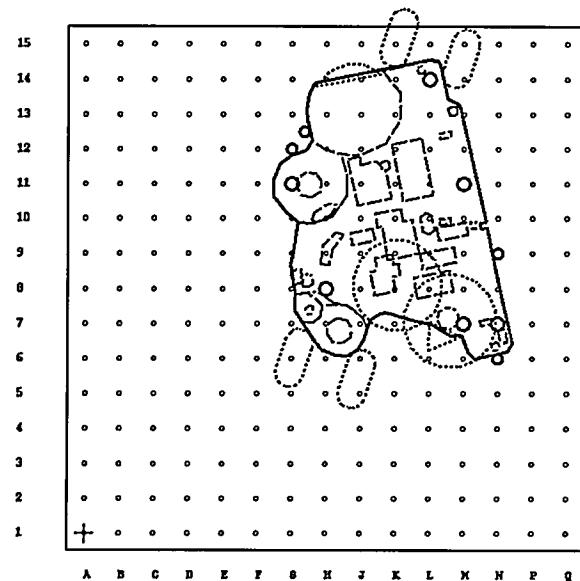
Some manufacturing scenarios require a part be flipped during assembly so that parts may be inserted from two different directions. An example scenario would insert the personal cassette player assembly, discussed in the previous section, into its case and then rotate the case to add external connector covers and labels to one of the case sides. A single pallet that could hold the product in two or more orientations may lower production costs.

Other manufacturing scenarios require the assembly of more than one product on a single assembly line. In one scenario, a company may manufacture a family of products on a single assembly line where slight differences exist between the products. In other scenarios, the products are dissimilar, but a single manufacturing line is desired to accommodate variations in market demand. In this case, a single pallet that could hold either product would enhance the manufacturer's ability to rapidly switch between products.

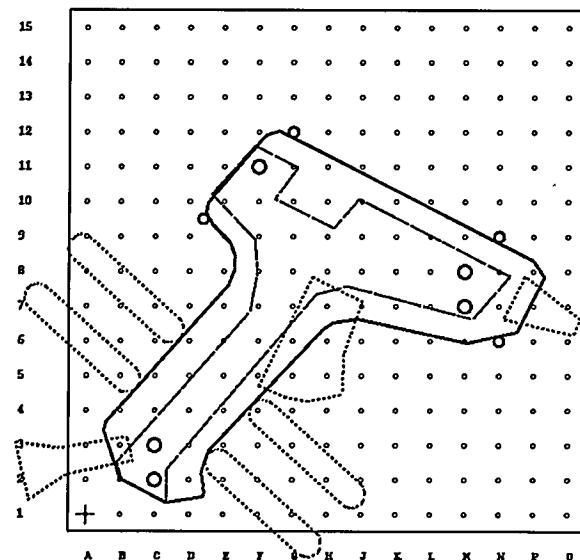
Suppose a company wishes to produce both cassette players and glue guns (see Figure 9), and would like to switch between the products on demand. HOLDFAST may be used to design a pallet capable of holding either assembly. This is accomplished by generating pallet designs for each problem individually, and then looking for pairs of designs that may be merged into a single pallet with a minimal number of pins. Figure 10 shows an example design for such a mixed-product pallet. Figure 11 shows the empty pallet, and the personal cassette player and the glue-gun loaded in the pallet. This pallet may be used to assemble either product, and allows switching between products in zero changeover time. This design requires only slightly more than half the total number of pins that are contained in the pair of individual pallets. The computer time required to find this pair (the best of 24 found) was a few minutes. Mixed-part pallets appear to be very difficult to design manually.

3 Design Algorithm

The HOLDFAST fixture design algorithm enumerates all feasible fixtures given a workpiece description, specification of the task constraints, and a description of the fixture kit components. Designing a fixture con-



(a) cassette player

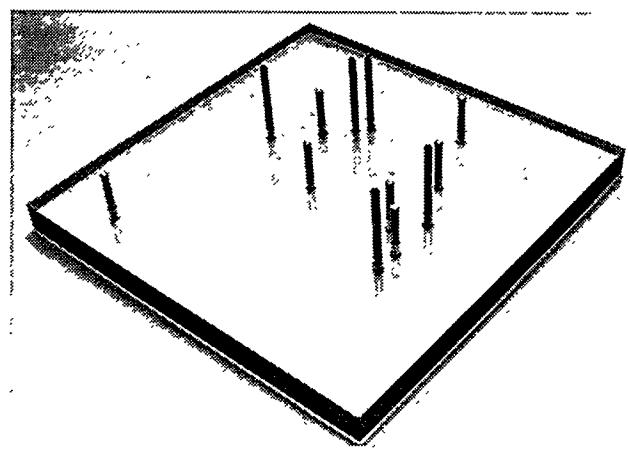


(b) glue gun

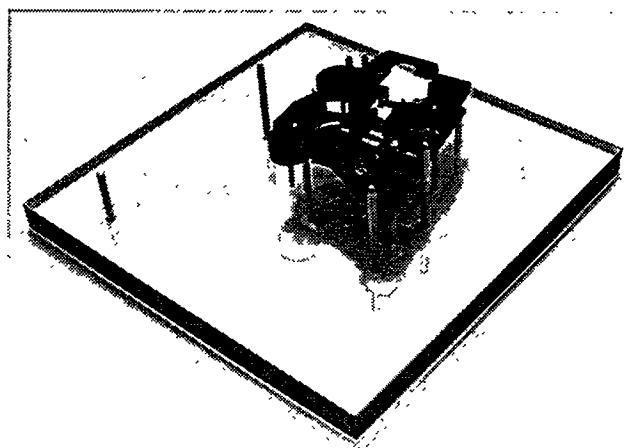
Figure 10: Optimal mixed-part pallet design for the assembly of a cassette player and a glue gun.

sists of designing the planar portion of the fixture that prevents workpiece motion in a plane parallel to the base-plate, and designing the vertical portion that constrains motion out of this plane. A loadability analysis is also performed if the fixture uses top clamps.

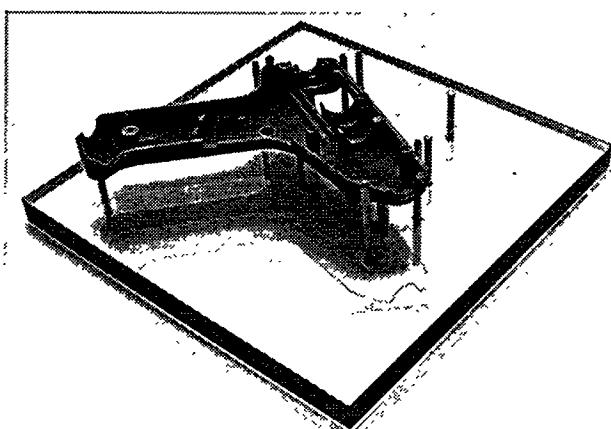
The planar fixture design algorithm enumerates all possible combinations of vertical edges that may be contacted by three lateral locators, then determines all



(a) pallet



(b) cassette player in pallet



(c) glue gun in pallet

Figure 11: Optimal mixed part pallet.

distinct lateral locator positions that contact the three specified edges, and finally for each lateral locator set determines all placements of the side clamp that will hold the workpiece in form-closure [Brost and Goldberg 1994]. The planar portion of the quality function is used to reject poor quality designs at this stage.

For each planar fixture design, the vertical fixture design algorithm enumerates either all support-pad/top-clamp pairs that vertically constrain the workpiece or a set of support pad locations that support the workpiece from below. If total vertical constraint is required, all support pad and top clamp locations are generated that allow pad/clamp pairs to contact horizontal workpiece surfaces. All sets of three pad/clamp pairs are then generated and evaluated using the vertical portion of the quality function; poor quality designs are rejected. If only support from below is required, the support pad location set is the convex hull of all valid support pad locations; again poor quality designs are rejected.

Finally, a loadability analysis is performed for those designs that use top-clamps to determine if the workpiece can be loaded into the fixture vertically and the top-clamp arms rotated into place. Pallet fixtures are assumed to be inherently loadable.

In order to produce a valid fixture design as quickly as possible, HOLDFAST interleaves this analysis so that as soon as a valid planar fixture design is generated, vertical supports are added to complete the fixture design, loadability is assessed, scoring is completed, and the result is displayed to the user.

There is substantial literature on fixturing; we only refer to a sample here. Process considerations have been studied by [Englert 1987], [Hayes and Wright 1989], and [Chang 1992]. Prior design algorithms include those by [Sakurai 1990], [Kim 1993], and [Baraff *et al.* 1994]. Algorithms that are foundational for HOLDFAST include [Brost and Goldberg 1994] and [Wallack and Canny 1994]. See [Brost and Peters 1995] for a more detailed explanation of the design algorithm and its relationship to previous work.

4 Summary

Fixture design and fabrication costs may comprise a significant portion of the cost to manufacture a product. We have created a tool that can be used to reduce these costs. HOLDFAST designs easily fabricated fixtures that provide rigid constraint and deterministic location of the workpiece, obey all associated task constraints, are robust in the face of workpiece shape variations, are easy to load and unload, and offer good economic performance in a variety of business scenarios.

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