SIMJig - Smart Independent Minimalist Jig

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***Abstract*—One of the most crucial parts of manufacturing is fixing the workpiece. Proper fixturing enables accurate machining, assembly, etching, etc. Most modern fixturing devices are static and difficult to adapt to varying workpieces. This letter introduces a new concept for a fixturing device–the SIMJig–that automatically adapts its structure to fix a given workpiece. Custom fitting the jig clamps to a workpiece can greatly improve the stability and accuracy of the manufacturing process. Reconfigurability is achieved by a unique clamp and gear design, as well as one of two optional external driving mechanisms. In total, the SIMJig only uses three actuators to control multiple clamps. The design of the SIMJig, as well as the two external drivers, are fully detailed. The method of operation is described, along with explanations of how the SIMJig is initialized. Two algorithms are presented that detail how the clamp configuration is derived from the workpiece model, and how the SIMJig derives the optimal reconfiguration scheme to achieve the clamp configuration. The SIMJig doubles as a turntable, which allows it to collaborate with robotic arms to vastly increase their workspace. This is illustrated for a notoriously difficult task of gasket insertion, using the SIMJig and two robotic arms.**

***Index Terms*—Industrial robots, grippers and other end-effectors, mechanism design.**

I. Introduction

In manufacturing, one of the key components in many processes involves fastening the workpiece. This crucial step dictates the interaction between the workpiece and the tool, which is why high-quality fastening of the workpiece is key to creating products that perform consistently and accurately.

Many manufacturing processes involve workpiece fixation. These include milling, assembly, die pressing, printing, etching, welding, and many more. The more precisely a workpiece is maintained, and the more it can withstand external forces with minimal deflection, the better the end result will be [1]. For example, in a CNC milling operation that requires an accuracy of 0.01 mm, there is little tolerance for a workpiece to be shifted by the force of the milling tool. Because of the importance of the fixturing device to product performance, considerable research and development efforts have been engaged for quite some time [2], [3].

One way of achieving robust workpiece fixation is by using large clamps with a high squeezing force. However, using large clamps can impede the manufacturing process by blocking access to parts of the workpiece. This technique is generally only satisfactory for simple workpieces which are often unrealistic in manufacturing [4]. In addition, very high squeezing forces can damage certain materials, or cause strain that affects the process and eventually the product. A different way of achieving robust workpiece fixation is by carefully selecting the placement of clamps, where a relatively low squeezing force is applied which is still sufficient to withstand external forces [5]–[7]. The drawback of this method is that manufacturing processes rarely have the latitude to select clamp placements at will, since these are usually constrained by the fixing device (e.g., a parallel vice). Custom fixing devices may be tailored to specific workpieces during the manufacturing process. This vastly improves the fixing ability of the workpiece, but comes at a considerable price since it is costly to manufacture a fixing device adapted to one single workpiece, and no others.

Much modern research on fixturing devices and jigs revolves around improving their fixturing capabilities. Attempts include *active fixturing* [8], [9], as well as the computer aided design of jigs [10], [11] and the integration of sensors to create *intelligent jigs* [12]–[14]. There are also efforts to create more flexible jigs [6], [15], [16], which have unique advantages in terms of workpiece adaptation.

This letter presents a novel type of fixing device dubbed the Smart Independent Minimalistic Jig (SIMJig) that can automatically restructure itself to custom-fit a given workpiece Fig. 1. This type of device is also known as a reconfigurable fixturing device, or a reconfigurable jig [17]; the generally accepted distinction between the two is that a jig can not only hold the workpiece, but also guide a tool, which the SIMJig is fully capable of. These devices have been shown to be highly useful in various industrial sectors, including aerospace [18] and energy [19]. Papastathis *et al.* created a jig that has active, reconfigurable clamps [11]. They reported that their device reduces the force-induced deflection of a workpiece by 84.2%, compared to standard fixturing devices. However, their clamping elements are strictly orthogonal to the workpiece, and are placed manually about the workpiece perimeter. Their work nevertheless points to the value of carefully calculating the optimal clamping points, and the role of accurate positioning of the clamps for better results.

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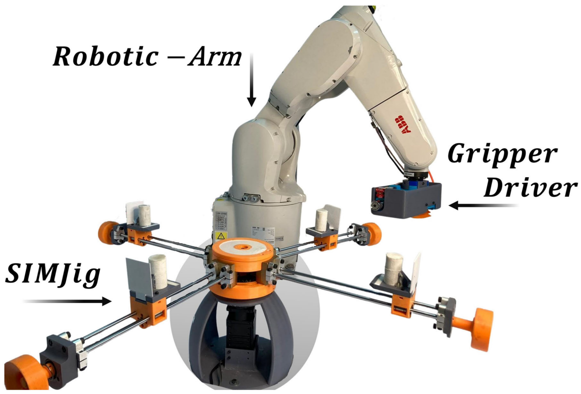

Fig. 1. The SIMJig system, shown here with three clamps and a centering clamp, driven by an external gripper-driver mounted on a robotic arm. Cooperation between the SIMJig and the gripper-driver makes it possible to control each clamp position associated with the SIMJig while using very few actuators.

By contrast, unlike existing reconfigurable jigs, the SIMJig is fully automated, and under-actuated; i.e., there are fewer actuators than degrees of freedom (DOF). The jig comprises several clamping surfaces and three actuators that restructure the device and the fixation of the workpiece.

This letter thus makes the following contributions:

1) The introduction of a novel fixation device– "SIMJig". This device allows autonomous, highly customized fixation of a workpiece, with easy adaptation to unknown and irregular workpieces. The SIMJig also serves as a turntable, making it especially useful as an integral part of the manufacturing process.
2) A unique, minimalistic design which enables control of a variable number (3-7) of two-DOF clamps, using only three actuators.
3) A unique method of cooperation between a jig and robotic arm. This novel cooperation consists of two robotic systems with independent as well as synergistic capabilities that ultimately creates high-quality fixtures while saving space and increasing system autonomy.
4) An algorithm for intelligent selection of clamp positioning, that optimizes configuration time and reduces workpiece vibrations and distortions.
5) An algorithm for device initialization and autonomous reconfiguration using a single sensor, which enables the system be almost fully independent while remaining extremely minimalistic.

II. Design

This section details the design of the SIMJig, as well as the basic design concepts for the external driving mechanisms. Specifically, we first detail the jig part of the SIMJig, which is followed by the clamp module of the SIMJig. The two ways of driving the SIMJig; i.e., with a gripper-driver or a static external driver are described next.

A. SIMJig

The SIMJig system was inspired by the design of a single-actuator robotic gripper [20]. The gripper implements a single motor and a cooperating robotic arm to change its configuration. The SIMJig system entails the cooperation between two unique sub-systems: the SIMJig itself and two flavors of external driver, as detailed below. The SIMJig contains a variable number of *clamps*, one *centering clamp* and the main motor, which rotates the whole SIMJig as a turntable. The specific design of the SIMJig allows the user to choose the number of clamps in the system, from two to seven. Adding or removing a clamp module requires partial disassembly of the SIMJig, thus making it a pre-determined decision, not part of routine operations. The higher the number of clamps, the more robust the grasp. However, adding more clamps increases the time it takes to transition from grasp to grasp. The SIMJig is designed to allow a planar grasp. While three grip points are sufficient to fix a planar object, more are typically employed to achieve a more robust grip. Since more than three clamps creates an *over-defined* system, flexibility is used to correct for small positioning and model errors. This flexibility is achieved by adding a thin silicon coating to the clamps to ensure equilibrium. As shown by [12], adding more contact points as supports while fixing a workpiece can dramatically reduce strain. The number of clamps are counted counterclockwise, starting from (but not counting) the centering clamp. The SIMJig central body is composed of two opposing face gears, which together form the *primary gear*. The face gears have 35 teeth and a pitch circle diameter of 70 mm. The central body also contains a circular slot, which serves as a rotational rail for the clamps. The clamps are prevented from rotary movement by a gear lock with the primary gear. The primary gear has significant backlash of 2°, mostly because the prototype was manufactured by 3D printing.

B. Clamps

Each clamp has two DOFs: the angle between the clamp and the centering clamp, and the distance between the clamp and the center of the SIMJig, which can be modified by an external driver. The centering clamp differs only slightly from the clamp in terms of a few minor changes in its design. The centering clamp is fixed to the central body, and serves as the reference angle $\theta_0 = 0$. The clamps and centering clamp are riders on linear rails. They are each driven independently by lead screws with a 2 mm pitch, so that one rotation of the external-driver motor invokes a 2 mm linear translation. When a lead screw is turned, the related clamp moves towards or away from the SIMJig. The clamps and centering clamp are typically connected by a 1:1 transmission that passes through the primary gear to the clamp's pinion, as depicted in Fig. 2. In the default state, when one lead screw rotates, the other lead screws rotate identically. The specific design of the clamps allows each of them to be driven independently. Each clamp's lead screw is connected to a pinion on one (proximal) end, and a hexagon head on the other (distal) end. The pinion has 10 teeth, a pitch circle diameter of 20 mm, and is normally meshed with the primary gear, and held in place by the spring-loaded hexagon head. As can be seen in Fig. 2, the hexagonal head can interface with the external driver. To improve interfacing accuracy, a universal wrench tool is used on the external driver, and the hexagonal head has

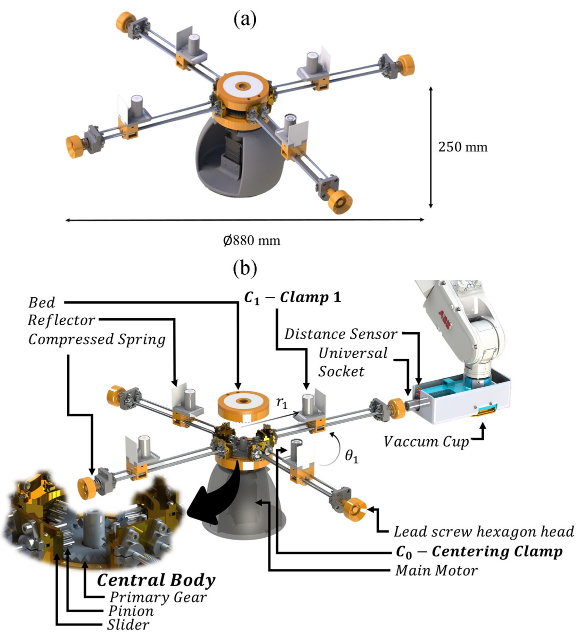

Fig. 2. A CAD rendering of (a) the SIMJig alone, and (b) a partially exploded view with an adjacent external driver. Each clamp of the SIMJig is driven by a lead screw which can be powered by either the pinion or the hexagonal head. Typically, the clamp pinions are meshed with the primary gear. This results in simultaneous retraction or extension of the clamps together. The gripper-driver (top right) is used to drive and calibrate the SIMJig, and to place (or remove) workpieces onto the SIMJig bed.

beveled guides. These beveled guides improve the concentricity of the external driver and hexagonal head interface. The use of the universal wrench tool allows for seamless integration, regardless of the hexagonal head orientation. Unlike the clamps, the centering clamp does not have a spring, and its pinion is always meshed with the primary gear. To drive a specific clamp independently, an external driving mechanism must be used. This can be either the static external driver, or the gripper-driver. These two mechanisms correspond to alternative ways to fully actuate the SIMJig's DOFs. A typical system will only have one. These two competing driver mechanisms are detailed next.

C. Gripper Driver

The gripper-driver is a robotic arm end-effector designed to drive the SIMJig and perform auxiliary tasks. The gripper-driver contains a single motor, a rotary encoder, and a standard vacuum gripper. The motor is used to interface with the SIMJig, and change its configuration. The vacuum gripper is used to perform pick-and-place tasks on workpieces. The gripper-driver necessitates the installation of a proximal robotic arm such as the ABB IRB1200-7 in Fig. 2.

In a typical work scenario, the robotic arm manipulates the gripper-driver to a predetermined start position. Next, a clamp is aligned with the gripper-driver. Then, the robotic arm makes a linear motion to interface the gripper-driver motor and the clamp. The gripper-driver motor's output shaft incorporates a universal socket tool, which locks into the hexagon head of the clamp's lead screw. When force is applied along the lead screw axis (toward the SIMJig's center), the lead screw is detached from the SIMJig's gear train. When the force is released, a spring returns the lead screw gear into the transmission. The SIMJig gear train serves the dual purpose of actuating the lead screws simultaneously and locking them rotationally. Once the lead screw is disengaged from the gear train, both the respective clamp angle and its distance from the center can be altered. When rotating the SIMJig's main motor in this configuration, the activated clamp stays stationary while the remaining sliders are rotated. This results in a change to the clamp's angle θ_i relative to the centering clamp θ_0. The gripper-driver contains a DC motor and a controller that enables it to rotate the clamp's lead screw, thus changing its distance from the center without affecting the other clamps. This process can be repeated for any clamp to change its angle relative to the centering clamp or its distance from the SIMJig's center. To reconfigure the SIMJig's grasp from one workpiece to another, a set of reconfiguration instructions are required. These instructions consist of a set of actions that bring the SIMJig to the desired final state, which is determined using Algorithm STL To Grasping Points (STGP). This algorithm needs to know the SIMJig's initial state, which can be inferred using a homing process (see Section III-D). The final step in the set of instructions is to connect the gripper-driver to the centering clamp's lead screw head. The centering clamp's pinion is always meshed with the primary gear. Thus, when the gripper-driver is connected to the centering clamp, actuating the gripper-driver's internal DC motor rotates the centering clamp's lead screw, and all of the other clamps' lead screws in turn. This procedure can be used to simultaneously retract the clamps from the workpiece for fixation. The gripper-driver also contains a distance sensor for the homing process, an ammeter to control the grasp torque on the object, and a vacuum cup for pick-and-place (P&P) action.

D. Static External Driver

In certain situations, the integration of the SIMJig with the gripper-driver as the working end-effector is impossible, due to constraints such as space, price and/or the need for P&P of complex objects. To respond to cases such as these, we developed an alternative driving mechanism. This static external driver has no P&P capabilities, and therefore requires an external and independent P&P system, which can be robotic or human. The static external robot interface contains two motors and a distance sensor. The method of operation is similar to the gripper-driver, with the important difference that the static external driver can only move along a single, set axis. The universal wrench tool moves along this axis to interface with the clamp lead screw head. One motor is attached to the universal wrench, and the other moves the first along a linear rail. An implementation of this interface can be seen in Section V.

III. Operating the Variable Structure SIMJig

This section introduces the basic principles of operation of the SIMJig. The technical design was detailed in Section II. Here the focus is on how the SIMJig adjusts the clamps to grasp a workpiece in a specific configuration. The SIMJig has two possible configurations, each with its own properties. The first configuration is *robot-aided*. In this configuration, the robotic arm manipulates a specialized gripper called a *gripper-driver*. The gripper-driver is used to partially actuate the SIMJig in its restructuring phase. The gripper-driver is also used to grasp and manipulate workpieces by placing and/or removing them from the SIMJig. The second configuration is *externally-driven*. In this configuration, a dedicated two-actuator device is rigidly fixed near the SIMJig, and serves in the restructuring phase. The specifics of the SIMJig operation and design are presented below. The features of the gripper-driver are presented in greater detail but apply to both configurations.

A. Method of Operation

To hold a new workpiece, the position of the clamps needs to be adjusted accordingly. Achieving the end-state position of the clamps requires an initial calibration process, as explained in detail below. At the start of the reconfiguration operation, the position of each clamp is corrected separately (radius and angle). The corrections adhere to a set of instructions as defined by Algorithm STGP and Algorithm Best Clamp Reconfiguration Order (BCRO). After correction of the clamps, the clamps and centering clamp are positioned on the workpiece boundary. The closing torque is measured using an ammeter connected to the gripper-driver's motor and the threshold current is calibrated using the motor tables. The gripper-driver is also used for P&P action, via a vacuum gripper and generator.

B. Workflow and Use Cases

The SIMJig system can be used to fix a wide range of bodies by following the workflow shown in Fig. 3. Typically, a jig in a production line fixes objects from the same model repeatedly. In this case, there is no need to restructure the SIMJig (change the clamp positions with respect to the centering clamp). Only a few final actions are required: placing the workpiece in the SIMJig, aligning the centering clamp with the gripper-driver, connecting the centering clamp's lead screw head to the universal wrench tool and radially closing all the clamps and the centering clamp on the workpiece. In the case where the workpiece model has changed, the SIMJig can autonomously adjust itself to the new workpiece. The user then needs to enter the following data: the number of clamps being used, the Standard Triangle Language(STL) model of the object and the desired plane to be grasped. Using these data, Algorithm STGP finds the qualitative grasping points on the workpiece boundary while simultaneously applying a homing process to find the updated position of the clamps. Next, Algorithm BCRO is used to determine the re-positioning process of the clamps. These interactions include a sequence of orders sent to the SIMJig and the gripper-driver while considering the configuration space and the design restrictions of the system. Each clamp is then aligned with the gripper-driver, before an angle and radius correction is applied based on the cooperation of the two subsystems. After all the clamps are positioned, these same four steps are sufficient to fix the workpiece. Each task and workpiece demands a different closure force. The value of the closure force is determined by the torque of the external driver motor. This torque is estimated using an ammeter, combined with the known current-to-torque ratio. The user manually enters the name of the STL file of the model they would like to fix and determines the work plane. This process is straightforward, and generally only takes a few seconds.

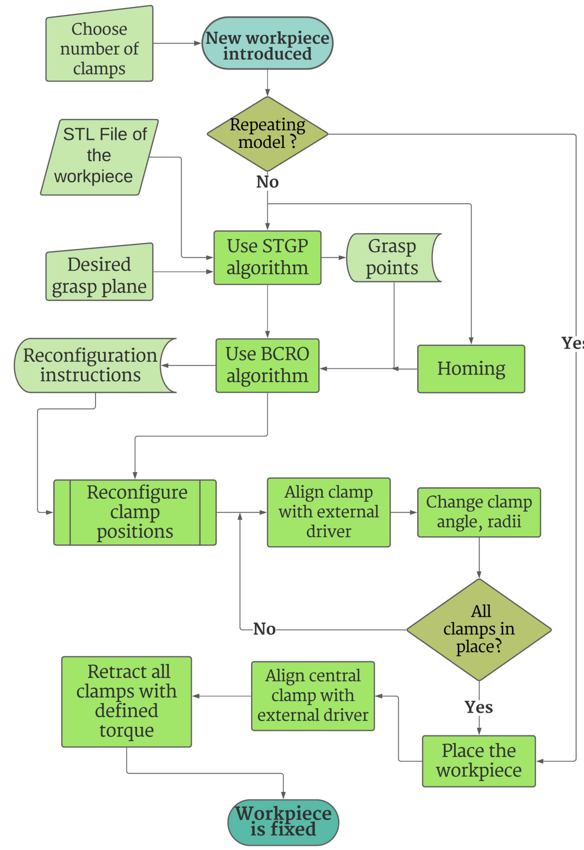

Fig. 3. A flowchart of the SIMJig work process. Starting from the top, the flowchart can be followed to result is the fixation of the workpiece.

C. Method of Actuation

The instructions contain sequential orders for the gripper-driver and the SIMJig. Fig. 4 shows an example of instruction execution from an initial state, Fig. 4 a, to a workpiece grasp, Fig. 4 g. The workpiece is a 3D printed PLA model with a mass of 300 grams. The closure torque was determined to be $3Nm$, yielding an average closure force of 75 N. Each state can be described as a vector of angles, the radii of the clamps, and the angle of the main motor ϕ. The initial state (Fig. 4 a) is $\{\phi^0, [\theta_1^0, \theta_2^0, \theta_3^0], [r_0^0, r_1^0, r_2^0, r_3^0]\}=$ $\{258\,°, 78\,°, 183\,°, 227\,°, 220\,\text{mm}, 204\,\text{mm}, 184\,\text{mm}, 136\,\text{mm}\}$. The final state (Fig. 4 g) is $\{\phi^f, [\theta_1^f, \theta_2^f\theta_3^f], [r_0^f, r_1^f, r_2^f, r_3^f]\}=$ $\{0°, 78°, 183°, 261°, 164\,\text{mm}, 148\,\text{mm}, 128\,\text{mm}, 154\text{mm}\}$. Each clamp that requires correction aligns with the gripper-driver according to Algorithm 2 (BCRO). In the example above, only clamp c_3 requires individual correction. In order to achieve gripper-driver and clamp alignment, the main motor rotates towards the value of the initial angle of clamp c_3– $\theta_3^0 = 227°$, Fig. 4 a to 4 b, so that the state is: $\{227°, 78°, 183°, 227°, 220\,\text{mm}, 204\,\text{mm}, 184\,\text{mm}, 136\text{mm}\}$.

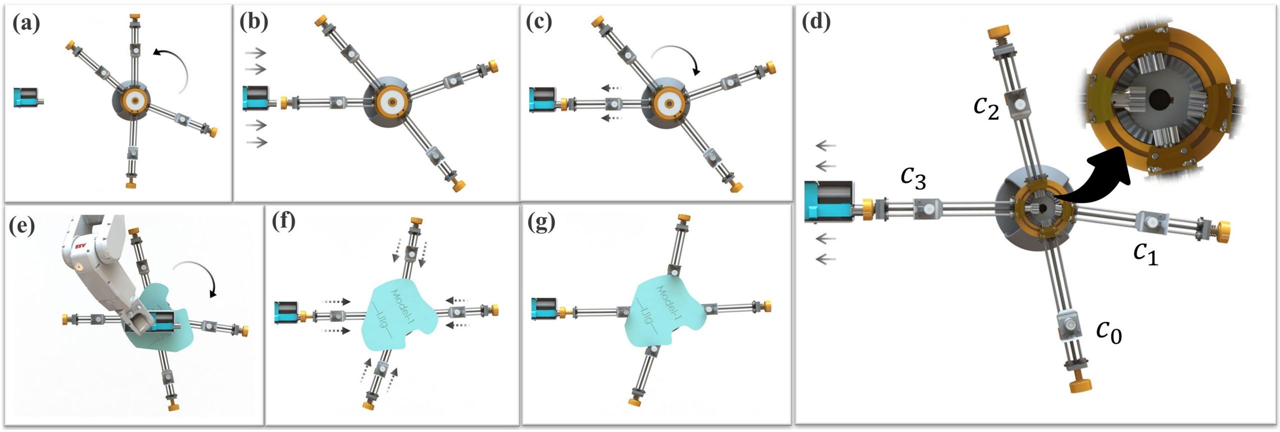

Fig. 4. An example reconfiguration from an initial state (a) to a workpiece grasp (g). In (b), the gripper driver is pressing clamp c_3 by decoupling its pinion from the primary gear, as can be seen in closeup (d). (c)-(d) show a correction to the relative angle and radius of c_3. (e) shows the gripper-driver placing the workpiece onto the SIMJig bed. (f)-(g) show the radial closure of the clamps and the centering clamp simultaneously on the workpiece.

Next, the gripper-driver connects to the clamp's lead screw head to disengage the clamp's pinion from the primary gear, Fig. 4 b to 4 c. Once the clamp's pinion has been separated, a correction to the relative angle of the clamp is made by rotating the main motor to the desired angle of clamp c_3– $\theta_3^f = 261°$, Fig. 4 c to 4 d. Next, a correction to the clamp's radius is made by the gripper-driver's motor, Fig. 4 c to 4 d. The new structure is now: $\{261°, 78°, 183°, 261°, 220\,\text{mm}, 204\,\text{mm}, 184\,\text{mm}, 210\text{mm}\}$ Crucially, note that the correction of the radius r_i considers the future correction of the centering clamp.

$$r_i^{correction} = r_i^{desired} - (r_0^{desired} - r_0^{initial}) \quad (1)$$

where r is the radius; i.e., the distance between the clamp and the SIMJig center. In this example:

$$r_i^{correction} = 154 - (164 - 220) = 210mm \quad (2)$$

After fixing the clamp positions, the gripper-driver picks up the workpiece from a predetermined position and places it on the bed, Fig. 4 e, before alignment with the centering clamp, Fig. 4 e to 4 f. For the purposes of this work, we assume that the gripper-driver picks the workpiece near its center of gravity, and places it on the SIMJig bed at an arbitrary yet fully-known pose. Finally, the gripper-driver's motor radially closes all clamps simultaneously on the workpiece with a preset closing torque. This leads to a global change in all the clamp radii of 56 mm, achieving a stable workpiece grasp; Fig. 4 f to 4 g.

D. Self-Identifications (initialization)

Since the SIMJig is designed to be an independent system, a homing process must be initiated to acquire the jig state. The purpose of the homing process is to gather data about the initial configuration of the system. The initial configuration is defined by the location of the clamps (angle and radius). The homing process is based on cooperation between the SIMJig and the gripper-driver. The gripper-driver has a Time Of Flight (TOF) type distance sensor (model VL53l0x). First, the robotic arm manipulates the gripper-driver to a predetermined position directed at the SIMJig center. Next, the main motor of the

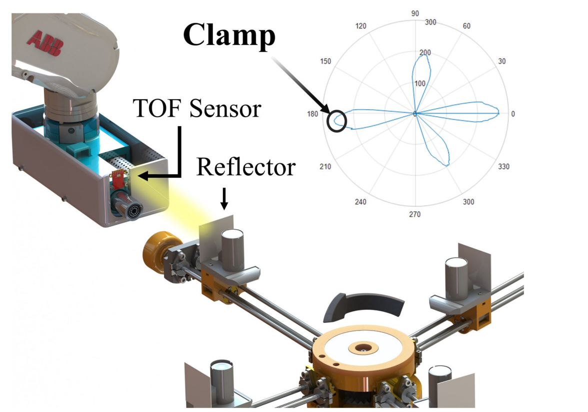

Fig. 5. The SIMJig during the homing process. The SIMJig is rotated in the proximity of the gripper-driver (top left). A TOF sensor on the gripper-driver maps the distance to the rotating SIMJig (top right). Analysis of the distance graph determines the individual clamps' orientations and radii.

SIMJig makes one full rotation; meanwhile, the gripper-driver takes samples from the TOF sensor while synchronizing the data with the angle of the main motor. During this process, values exceeding a predetermined threshold are cleared from the database. The data are then transposed into a coordinate system located in the center of the SIMJig. The transformation is straightforward since both locations (TOF, SIMJig's center) are known and constant. As can be seen in Fig. 5, each clamp can be identified as a local extremum. The main motor is a Dynamixel PM54 which has an absolute encoder. The rotation begins after the centering clamp is aligned in front of the gripper-driver (θ_0). To deal with measurement errors of the TOF sensor, a moving-average type smoother is applied using (3):

$$d_n^{new} = \alpha \cdot d_{n-2} + \alpha \cdot d_{n-1} + (1 - 2\alpha) \cdot d_n \quad (3)$$

where d is the measurement of the TOF sensor and α is a constant value calibrated to the system. After initially identifying the angle of each clamp, the SIMJig makes another rotation in which it measures approximately 200 samples of each clamp's estimated angle. This process leads to a better estimation of each clamp's radius compared to the radius measured previously, using the following estimator:

$$\hat{d}_k = \hat{d}_{k-1} + \frac{1}{k} \cdot (d_k - \hat{d}_{k-1}) \mid \hat{d}_1 = d_1 \tag{4}$$

where d_k is measurement #k of the TOF sensor, and $\hat{d}_k$ is the estimation of the real distance of measurement number k. The advantage of this method over dedicated sensors (e.g., encoders on the clamps) is its ability to achieve full self-identification using only one low-cost sensor, independently of the number of clamps. The process duration is generally 35-65 seconds, depending on the number of clamps.

IV. Fixation Planning

A. System Configuration Space

This section describes the execution of the fixation process. First, the configuration space of the SIMJig must be defined. The number of clamps N can range from two to seven. c_i defines a given clamp, counting counterclockwise from the centering clamp c_0. i is the index, $i = 0 \ldots N$. Note that this work does not deal with the complex problem of determining the optimal number of clamps. The current state of the clamps Sb is aquired by the homing process. Sd is the desired state of the SIMJig. As mentioned above, each clamp c_i is defined by two parameters: θ_i is the angle between the clamp and the centering clamp. r_i is the distance between the clamp and the center of the SIMJig. These parameters constitute the design configuration space C:

$$\begin{aligned}
&\{\theta, r\} \in C \\
&\quad \forall i \in [1 \ldots N-2], \theta_i \in [\theta_{i-1} + \psi, \theta_{i+1} + \psi] \\
&\quad \theta_i \in [\theta_{i-2} + \psi, 2\pi - \psi] \mid i = N-1 \\
&\forall i, r_i \in [L_{min}, L_{max}]
\end{aligned}$$

These conditions consider the length of the linear rail and the minimum possible angle between two clamps, where the latter is a function of the rider width. ψ represents the minimum angle between two clamps and is equal to 20°. L_{max} is the maximal extension and L_{min} is the minimum restriction of the clamp. ψ, L_{max} and L_{min} are constants within the design and are equal to $380\,mm$ and $50\,mm$ respectively. The current design can fix workpieces with principal diameters in the range of $[100\,mm, 760mm]$. This range can be easily adjusted by replacing the clamps and/or extending the rails.

B. Formulation of the Fixation Plan

The next step is to define the fixation points on the workpiece via Algorithm 1 (STGP) which is designed to achieve a robust grasp. The algorithm inputs the data of the workpiece model as an STL file; namely, a 3D model which consists of triangles that define the object. First, Algorithm 1 (STGP) discretizes the STL file to increase its resolution. Next, the STL is converted to a point cloud that is then filtered using the *convex hull algorithm*, to separate the boundary of the workpiece from other irrelevant data. At this point, the users define the plane they would like to fix, taking into consideration the height of the clamps and the preference for a flat surface on the SIMJig's bed. A set of optional points for grasping, defined as B, is then obtained. Finally, the algorithm runs an optimization process using a Monte Carlo (MC) algorithm to achieve a high-quality grasp. From the set of points B, many combinations are verified and stored as MB, along with a score W, defining the quality of the grasp and the inclusion in the configuration space.

Algorithm 1: STGP - STL To Grasping Points.

Input: STL model, C, Desired grasp plane N
Output: Grasp points on the model boundary - GP
Initialization: arrays $M, MB, TMB \leftarrow 0$
Discretize the STL and convert to point cloud
Store in array B points which are on the boundary of the desired grasp plane
LOOP Process
for every iteration i **do**
  From B randomly select $N+1$ points, store in TMB
  if ($TMB \in MB$) **then**
    continue
  else if ($TMB \notin C$) **then**
    $W_i = -\infty$
  else
    Compute weight W_i, wrench space sphere method
  end if
  $MB_i \leftarrow TMB$
end for
$GP = MB_{argmax(W)}$
return GP

There are many grasp quality measures, which are not evaluated here. The procedure presented in this letter uses the *wrench space sphere radius* quality measure [21], [22], although any other quality measure can be used. The combination with the highest quality score is the best grasp configuration out of all the combinations within MB. The more combinations are tested, the better the resulting grasp. This is an Anytime algorithm that returns the best result found to date. To save time, this algorithm can be run in parallel to the homing process, since they are independent of each other. The algorithm will return the best result once the homing is complete.

C. Motion Planning for Execution

After inputting the grasping points, a motion planning program must be applied. The motion planning program is comprised of instructions to correct the clamp angles and radii. The objective of the program is to find the best order in which to reconfigure the clamps. The cost of reconfiguration is governed by two parameters: a. the number of interactions with the external driving system, and b. the *Joint value*; i.e., the total rotation of the main motor.

In terms of restructuring time, the joint value has considerably less impact than the external driving system interactions.

Algorithm 2: BCRO - Best Clamp Reconfiguration Order.

Input: Initial configuration S_b, desired configuration S_d, minimum angle between two clamps ψ, initial centering clamp angle ϕ, array of all possible permutations F
Output: F_{best} - best clamp reconfiguration order
Initialization : $\forall i \in [1 \ldots K], W_i \leftarrow 0$
LOOP Process
1: **for** each permutation i **do**
2: **for** each digit j **do**
3: **if** $(Sb_{1+F_{i,j}} - Sd_j > \psi)$ **then**
4: $W_i = W_i + min(||Sb_{F_{i,j}} - \phi||, \ ||\phi - Sb_{F_{i,j}}||)$
5: $W_i = W_i + ||Sb_{F_{i,j}} - Sd_j||$
6: $Sb_{F_{i,j}} \leftarrow Sd_j$
7: $\phi \leftarrow Sd_j$
8: **else**
9: $W_i = \infty$
10: **break**
11: **end if**
12: **end for**
13: **end for**
14: $F_{best} = F_{argmin(W)}$
15: **return** F_{best}

Therefore, the effort to reduce the restructuring time centers on reducing the number of interactions. Theoretically, the re-orientation of the clamps should be very simple. In fact, if the order of re-orientation is selected wisely, each clamp only needs to be re-oriented once. This is shown in [23]. Since the design can contain $N = 7$ clamps at most, all the clamp-order permutations can be taken into account. All the possible permutations are represented in array F. The number of permutations is denoted K.

$$F_i \in [1 \ldots K]$$

Each permutation includes all the clamps that need correction:

$$F_i = \{j \in [1 \ldots N] \mid Sd_j - Sb_j \neq 0\}$$

The output of this algorithm is the best order to reconstruct the clamps -F_{best} This algorithm is based on the assumption that a solution in which no more than one iteration per clamp is required exists. The upper bound of the size of F_{best} (the number of interactions) is $N + 1$ and the lower bound is one. The case of one interaction only occurs when the system must re-grasp repeating workpiece models. In this case, it is sufficient to connect the gripper-driver to the centering clamp. Algorithm 2 (BCRO) calculates the joint value (lines 4-5) of each permutation and makes sure no collisions will occur during the adjustment under the limitations of the configuration space (line 3).

Algorithm 2 (BCRO) returns F_{best}, which is used to generate the instructions. The BCRO taps few resources due to the upper bound on the number of clamps. Assuming all clamps require correction, the value of K is:

$$nPg(n, g) = \frac{n!}{(n-g)!} \quad (5)$$

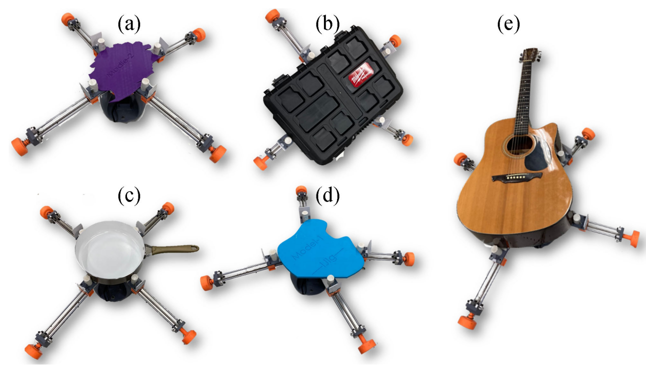

Fig. 6. Examples of various objects that can be fixed by the SIMJig, demonstrating its versatility. These include (a) an irregular PLA piece with castellations, (b) a plastic container lid with a gasket, (c) a frying pan, (d) an irregular PLA piece with varying curved edges, (e) a guitar.

where nPg represents the number of ways to choose a sample of g elements from a set of n distinct objects where order does matter.

V. Fixing the Workpiece

A. Superiority Over Existing Active Fixture Devices

Today's active fixation devices allow the fixation of varying bodies, but are limited with respect to the size of the workpiece. In addition, active fixation devices are characterized by many actuators (one actuator for each DOF), as seen in [8]. The SIMJig has a large workspace and absolute control over the position of the adaptive number of clamps while using only three actuators. As shown in Fig. 6, the device is capable of fixing bodies with widely different geometries and sizes. Objects 6(a) and 6(d) were inspired by the workpieces that [8], [9] suggested as examples of shapes that can be uniquely fixed by active fixturing devices. The solutions suggested by [8], [9] have very small workspaces and more actuators compared to our design. Objects 6(c) and 6(e) are examples of curved shapes with different sizes that can be challenging to fix by ordinary clamps or an X-Y table, which primarily grasps shapes with parallel, orthogonal edges. Many articles dealing with fixation devices have discussed how to reduce the loads on the workpiece to reduce vibrations and distortions [12]. Our device allows for the intelligent positioning of the clamps to avoid stress concentration points through the incorporation of grasp quality measures. This positioning dramatically reduces the force required to resist external forces and moments and prevents plastic deformations [21] [22]. The lid shown in Fig. 6(b) is a real workpiece that a manufacturer could not properly grasp with ordinary clamps, despite its generally rectangular shape. The closing forces required to resist external forces during the insertion of the gaskets were too large and caused plastic deformations. Using the SIMJig and intelligent clamp positioning, the lid could be grasped and the gasket inserted without damaging the workpiece (see accompanying video). The SIMJig's unique design enables re-grasping of repeating objects by moving all the clamps simultaneously. This makes it eminently suitable for production lines.

B. Using the SIMJig as a Collaborator

The SIMJig system can rotate the bed while fixing the workpiece and function as a turntable. This is an advantage in the case of complex assembly tasks. A routine task such as putting a gasket in a lid which is typically performed manually due to its complexity only requires the cooperation of two robotic arms and the SIMJig using the configuration of static external driver as seen in the accompanying video. The workspace of this type of action is not fully accessible without using a turntable. Below we take the example of different models of plastic lids manufactured by Keter plastic Ltd. Numerous assembly tasks can be facilitated by the SIMJig. Gasket insertion was selected because it consists of the automation of a complex operation that does not require much precision. The SIMJig system can adjust itself to fix different types of lids in a size range of 200mm-600 mm. Once the SIMJig has contracted and the workpiece is fixed, one arm inserts the gasket following the slot and the second arm guides the gasket while the SIMJig rotates with the fixed lid. The three working together associate two crucial capabilities: the ability to fix different lids using the same system, and a reduction in the required workspace by more than 70%, which is priceless in dense production lines.

VI. Conclusion

This letter presented a novel type of fixturing device for manufacturing. The device has only three actuators, but can sequentially reconfigure itself to securely clamp a wide variety of workpieces. Basic algorithms determine the clamping points based on the object's geometry and the SIMJig's physical limitations. The SIMJig can also be used as a turntable in conjunction with the tool (e.g., robotic arm and drill) to increase workspace and manufacturing dexterity.

The SIMJig is currently only a proof of concept of these novel design concepts and the algorithmic implementation. Hence, the precision of the SIMJig is poor compared to fixturing devices on the market and is estimated to have a mean error of several millimeters, which is far from acceptable for most manufacturing tasks. However, low precision is not an inherent trait of the design, but rather stems from the deliberately simple design and manufacturing methods (much of the SIMJig is 3D printed). Gear backlash, a lack of structural stiffness, and imprecise parts contribute to the poor precision, but can all be improved drastically with better design and manufacturing.

In future work, we will focus primarily on "industrializing" the SIMJig by optimizing the design for robustness and precision. By reducing the flexibility and backlash we expect the precision of the workpiece fixturing to increase dramatically. Fixturing precision will be exhaustively examined, as part of the ultimate design goals. We also plan to work on more robust clamping algorithms that take the specific forces expected to act on the workpiece into account. We will also investigate the possibility of releasing and re-clamping the workpiece at different points to tailor fixturing to the manufacturing step.

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