2019-01-1374 Published 19 Mar 2019

Collaborative Robotic Fastening Using Stereo Machine Vision

Ryan Haldimann Electroimpact Inc.

Citation: Haldimann, R., "Collaborative Robotic Fastening Using Stereo Machine Vision," SAE Technical Paper 2019-01-1374, 2019, doi:10.4271/2019-01-1374.

Abstract

With typically over 2.3 million parts, attached with over 3 million fasteners, it may be surprising to learn that approximately two out of every three fasteners on a twin aisle aircraft are fastened by hand. In addition the fasteners are often installed in locations designed for strength and not necessarily ergonomics. These facts lead to vast opportunities to automate this tedious and repetitive task. The solution outlined in this paper utilizes the latest machine vision and robotics techniques to solve these unique challenges. Stereo machine vision techniques find the fastener on the interior of an aerospace structure and calculate the 6DOF (Degrees of Freedom) location in less than 500ms. Once the fastener is located, sealed, and inspected for bead width and gaps, a nut or collar is then installed. Force feedback capabilities of a collaborative robot are used to prevent part damage and ensure the nut or collar are properly located on the fastener. This type robot also opens up the possibility of interacting more closely with humans as fastening can be done simultaneously with other manual assembly processes. This paper outlines how automated fastening can be achieved using an end effector weighing less than 14kg by leveraging the capabilities of a collaborative robot and advanced machine vision techniques.

Introduction

Since the Wright Flyer in 1903 the assembly of aircraft has been done primarily by hand. Structural components have advanced using modern manufacturing techniques, from canvas covered wood to riveted sheet metal and now composite parts, however the assembly of these parts into an aircraft is largely done by hand. In the last 15 years processes for primary airframe assembly have moved from manual drill jigs to robotic processes. After primary structures are assembled by automated processes, putting the nut on a threaded fastener or swaging the collar on a lockbolt type fastener is still largely done manually.

There is good reason why it is still done by hand; aircraft are optimized for weight and flight first and human assembly second. Assembly by robot isn't typically designed in from the beginning and when it is, the access requirements can be so restrictive that it makes the plane structurally unsound or too heavy. Automation in this limited space requires many degrees of freedom, touch and vision that mimic the dexterity and senses of the human currently assembling it. The soft touch of a human also prevents damage to delicate finishes that inhibit corrosion and protect the airframe. Minor damage to these finishes could cause fatigue issues or airframe failure.

The challenge was to develop an automation system that is similar to a human in flexibility and sensitivity with the ability to locate and fasten inside a tightly contained space.

Automation Approach

Motion Platform

The motion platform used to position the EOAT (End of Arm Tooling) had multiple design constraints. As the goal was to do that same work that humans do, it needed to have many degrees of freedom to work in the same spaces, function alongside humans, avoid part damage and have enough rigidity and power to seat collars and nuts. As the system needed to detect external forces from part collisions or humans, the Kuka IIWA collaborative robot with direct torque measurement at each joint was selected.

Accommodate When a human installs a collar on a pintail type fastener, the puller is positioned at the end of the fastener and the tool is slid onto the fastener tail adjusting the angle of the puller when resistance is felt until it is fully seated. To achieve a similar methodology the robot includes a control paradigm that models the EOAT as a spring mass damper system which allows the robot to emulate the same process a human uses. To accurately do this the moments of inertia must be accurately determined and there can be no external forces applied to the EOAT. Cabling that applies an external force or changes to the mass of the EOAT caused by fastener insertion or use of sealant must be accounted for. The spring mass damper control system also allows for the application of external forces, such as clamp force. Applying a clamp force in software negates the need for a mechanical implementation of clamping. A cyclic load and moment can also be applied to the tool point emulating the human process of feeding the collar, nut or swaging tool onto the fastener.

Collaborate Aircraft are optimized for flight with minor concessions made for manufacturability by humans. This means that any automation introduced may require the flexibility of human dexterity to access all fasteners. To date humanity has not produced a robotic arm with the strength and senses of a human. The Kuka robot selected has the most sensitive torque detection, 0.8Nm at axis seven and 6.4Nm at axis one.

It uses built in using secondary torque monitoring at each joint as opposed to using the motor current/torque constants which are not as precise as direct measurement and deemed inferior to direct measurement. Being able to most sensitively measure forces and compare those with the expected force modeled in the control allows the robot to detect collisions with both parts and humans. Being able to work alongside humans simplifies the workflow as it does not displace manual operations for safety concerns.

Locate Using Stereo Vision

Aircraft structures by very nature are large assemblies of sometimes very flexible parts. Assemblies are typically over 30ft long and the location of individual components relative to the global coordinate system can be effected by temperature, manufacturing tolerance stack-up, assembly order and part strain imparted by assembly. The specific location of the fastener in the global coordinate system could vary by as much as ±0.5”. Additionally the access restrictions of some fasteners due to surrounding components leave <0.06” clearance, making installation even by hand difficult.

The use of a location system that has the ability to search a volume greater than the positional accuracy of the positioning system, ± .196”(5mm) and part uncertainty combined and doesn’t require physical access to the space can be solved using a machine vision system to locate the fastener. The vision system would need to search a large volume and accurately locate the fastener to place the collar or nut successfully. To locate the fastener in 6DOF space, 3D stereo machine vision techniques were employed.

The vision system is comprised of 2 cameras separated by some baseline distance: D_1(*Figure 9*). The optical path is bent *(Figure 2)* to achieve the separation required to achieve accuracy specifications but allow for mechanical integration into the automation processes.

FIGURE 1 Stereo Vision System Back

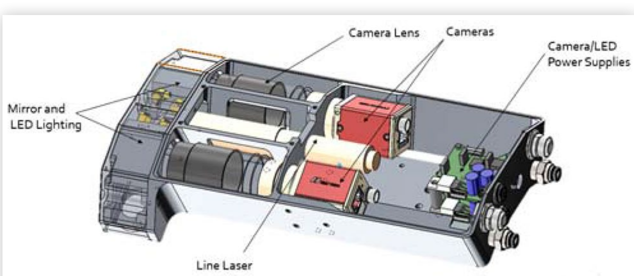
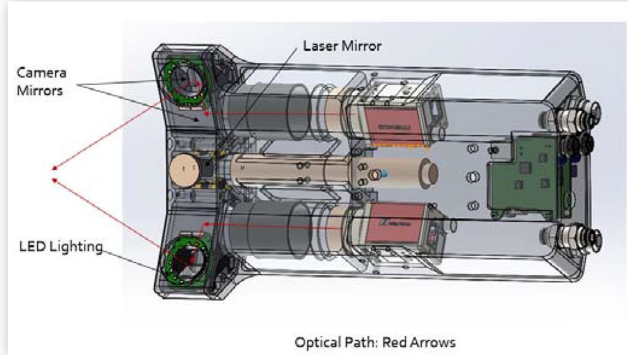
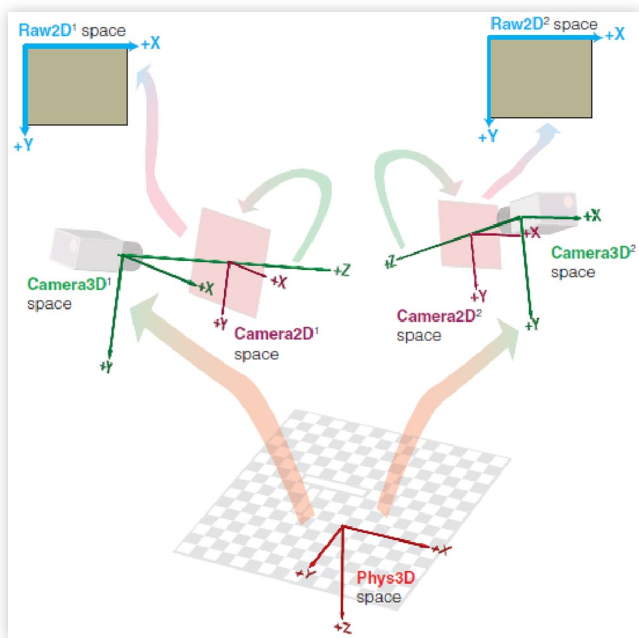


FIGURE 2 Stereo Vision System Front



Calibration of 3D Vision To accurately locate the fastener the vision system must first be calibrated. This is done using machine learning techniques to determine the 12 parameters per camera to fully define the transformation between a cameras 2D image space to the physical 3D space. These parameters can be broken into two groups; 6 extrinsic parameters that define the location of each camera to the physical world and 6 intrinsic parameters that define characteristics of the camera and lens setup. Intrinsic parameters define the focal length of the lens, scaling of pixels, image offset and a radial distortion coefficient for the lens. Extrinsic parameters define the position and rotation of the camera in space. To determine the 12 parameters for a single camera a number of images are acquired using a checkerboard calibration plate with an origin fiducial marker (*Figure 3*). The plate is moved in 6DOF space with known offsets and then with unknown rotations. After the intersections are located, a least

FIGURE 3 Stereo Camera Calibration



squared error function is minimized using gradient decent to solve for the 12 linear parameters. This calculation is common in machine vision software and its results are not investigated here. What these parameters define are important to understanding how this 3D stereo vision functions.

Accuracy One Camera vs. Two Cameras. Traditional methods using correspondence points to locate an object in 3D with 2D cameras require a minimum of 2 images. A single camera can be used at multiple locations or N cameras with fixed relation to each other can be used. Utilizing a single camera in multiple locations has the benefit of less hardware and has the ability to dynamically position the camera based on material constraints located in the working envelope i.e. clips and brackets for ancillary components. However it includes in its measurements the positional error of the positioning system. Each image taken includes the error of the motion platform in its results. Any images taken and used to calculate the extrinsic parameters would include positioning system error. For this reason an external stage is used to move the calibration plate, resulting in a very accurate calibration of the cameras relative to each other. To determine their location relative to the tool flange of the robot a series of measurements are taken at various poses of the robot. The 6DOF transform to the camera system from the robot flange is then calculated using gradient descent.

Use of Camera Extrinsic Parameters to Locate Fastener. Finding an object in 6DOF space is a much researched and understood problem in machine vision. The common approach is to use correlation points on the object to map between expected and actual space. While this approach works for objects with easily identified vertices, fastener tails are largely cylindrical and have no unique points to assist in identification, making correspondence correlation ineffective.

By using the extrinsic parameters of the camera found in calibration and performing simple Euclidean geometry the axis and end of the fastener can be located (*Figure 8*). From the 2D image of the fastener the centerline is located by

FIGURE 4 Part Location Using Correlation Points

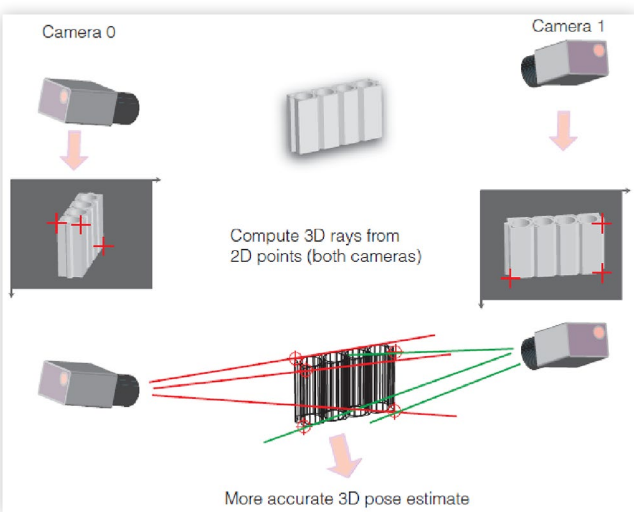


FIGURE 5 Raw Image

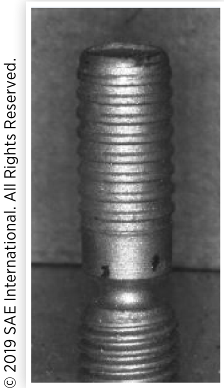
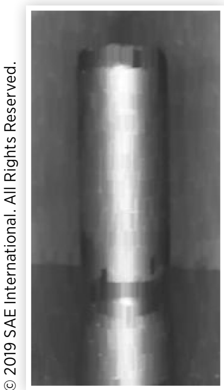


FIGURE 6 Processed Image



first passing a convolution kernel over the image that removes the fastener threads or ridges on a pull tail type fastener (Figure 5, 6).

Removing this high frequency feature allows for particle analysis to be performed to find a line representing the center of the fastener and its angle (*Figure 7*). The cylindrical geometry of the fastener ensures that the light reflected back to the camera is centered on its axis.

Now that the centerline of the fastener is found in 2D space, a 3D plane can be constructed that is defined by the centerline of the fastener and the camera extrinsic origin

FIGURE 7 Fastener Center Line

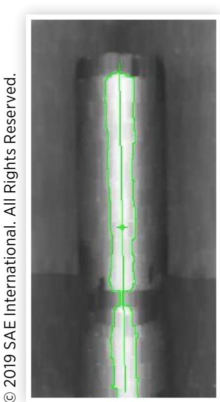
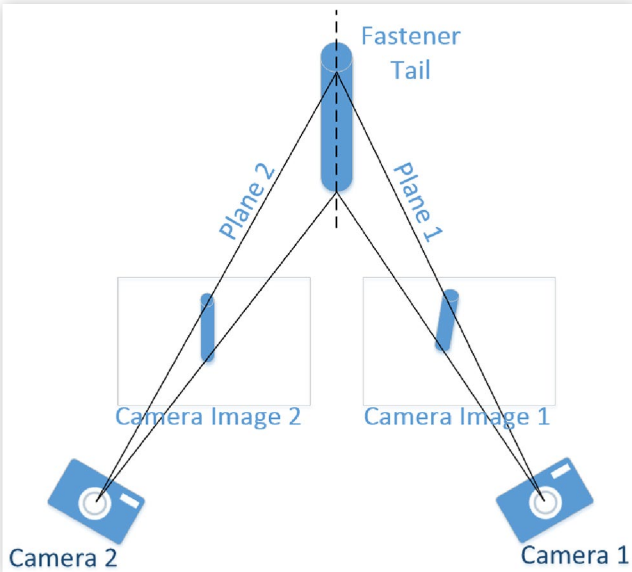


FIGURE 8 Stereo Camera Geometry



parameter. This is done for both cameras to create two intersecting planes (Figure 8). The location at which these planes intersect is the centerline of the fastener in 3D space.

There is some error related to the angle the cameras are to each other and the baseline distance between them. This is characterized by ϵ_x*and* ϵ_y in equations (2) and (3). Of note is that the error is symmetric when the cameras are at 90° angles to each other.

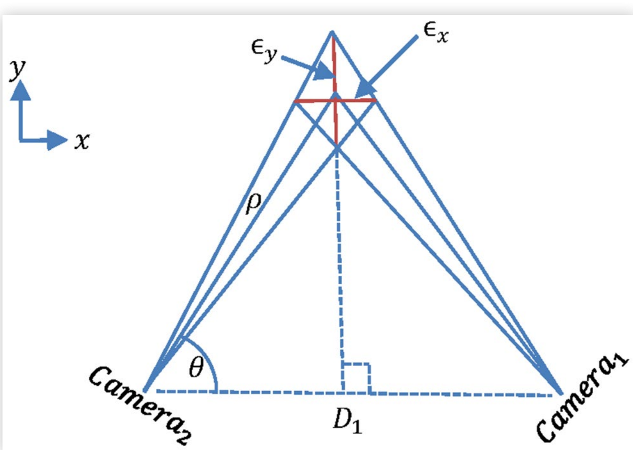
$$\mathrm{FOV_x} = \text{Camera Field of View}$$

$$\rho = \mathrm{atan}\left(\frac{FOV_x * \cos(\theta)}{Pixels_x * D_1}\right) \quad (1)$$

$$\epsilon_x = \frac{D_1\left(\tan(\theta-\rho) - \tan(\theta+\rho)\right)}{\tan(\theta+\rho) + \tan(\theta-\rho)} \quad (2)$$

$$\epsilon_y = \frac{1}{2} D_1(\tan(\theta+\rho) - \tan(\theta-\rho) \quad (3)$$

FIGURE 9 Camera Error



Experimental Accuracy

Accuracy was measured by placing two cameras with a baseline D_1 of 10" and a θ of ~60° on a moving plate. To measure translation a digital caliper was attached to the moving. The plate and cameras were calibrated using a series of translation and rotations of the calibration plate. After calibration a series of images were captured of a fastener at different known distances to characterize the accuracy. The accuracy had a predictable trend indicating that not all factors were accounted for but was well within the requirements of the system.

Sealant Application

The EOAT tooling also contains a sealant applicator. The applicator consists of a pressurized cylinder of sealant that is extruded from an orifice tip that is self fixturing against the shank of the fastener (*Figure 10*). Prior to installing the collar or nut the robot is moved along the fastener axis found using the stereo vision camera to apply a stripe of sealant on the fastener. During the robotic move to apply sealant a color sensor is used to verify that the sealant is applied to the fastener prior to installing the nut or collar.

FIGURE 10 Sealant Application and Inspection

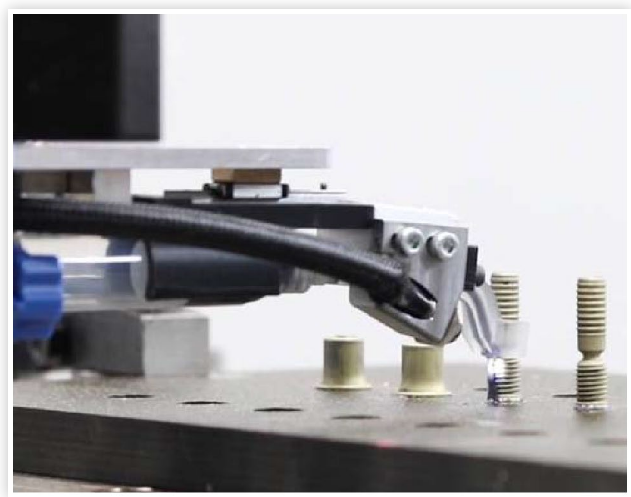


FIGURE 11 System Accuracy

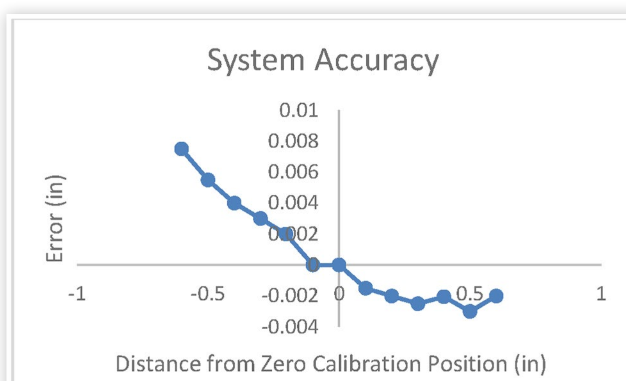
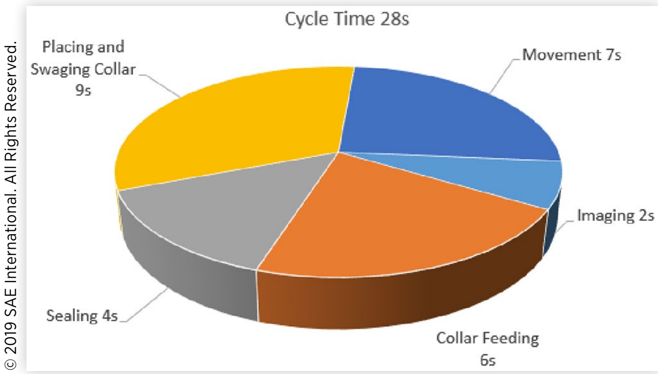


FIGURE 12 Cycle Time



Summary/Conclusions

While this system does fulfil its requirements, overall cycle time of 28s could be improved, especially when compared to a cycle time of 8-12 seconds for human installation. The positioning speed of the system could be improved by decreasing the EOAT mass and collar feed could be done while moving to place the collar.

With very few compromises the system described can position itself relative to a fastener, apply sealant, detect sealant, and install a collar or nut to aerospace standards. The use of a collaborative robot facilitates close interaction with humans and the ability to detect part collisions when positioning. In conclusion this system could enable the automation of large quantities of fasteners currently installed manually.

Contact Information

Ryan Haldimann
Principal Machine Vision and Controls Engineer
ryanh@electroimpact.com

Definitions/Abbreviations

EOAT - End Of Arm Tooling

FOV - Field of View

DOF - Degree of Freedom

Convolution Kernel - Array of constants to multiply surrounding pixels by which are then summed to achieve a new pixel value

ISSN 0148-7191