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RobSurf: A Near Real Time OLP System for Robotic Surface Finishing

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Abstract

In this paper we will discuss the development and use of a CAD based robot path and process-planning environment for surface finishing of conventional (metal) and non-conventional material (fiberglass composites) workpieces. This system is based on a modular and parametric approach process modeling for experimentation in determining "optimum" process parameters. It can operate upon workpieces of various characteristics due to the integrated soft setup methodologies.

RobSurf is a surface modeling and path generation system developed specifically for experimentation and identification of process parameters for processes associated with surface finishing. Using a coordinate measuring device interfaced with AutoCAD, the system is capable of generating a CAD model of any surface through reverse engineering techniques and generating native robot control code with embedded process parameters for various routines such as fill, form, and fair as well as information of the process tooling employed. The generated robot control code is then transferred to the robot controller via an RS-232C interface connection.

1 Introduction

Automated surface finishing, ASF, is a process that could be widely used in the manufacturing technology industry for a variety of applications ranging from aerospace to automotive to ship industry, etc. This is a need that is partially addressed in industry through the robotic automation of processes

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such as deburring, grinding, and finishing. However, little research and development has been performed in the actual surface finishing process itself.

The motivation, as in many applications, stems mainly from the current manual fairing process and the complexity associated with automating this process. In the manual arena, the factors that contribute to the need for the development of a robotic ASF workcell are health related. These are the exposure of workers' hands and arms to mechanical impact, vibrations, and the repetitive motion. These factors lead to workers' fatigue and disability, human errors and inconsistencies. In addition to health reasons, a shortage of skilled labor for surface finishing has been observed according to the sponsoring agencies.

In the automation arena, factors that contribute to the need for a robotic ASF workcell are the complexity of the contoured surfaces to be finished, the lack of effective means for process monitoring, lack of feedback and real time adaptive control techniques and the slow and difficult programming process.

2 Background

The Automation and Robotics Research Institute (ARRI) is an applied research center in the College of Engineering of the University of Texas at Arlington (UTA). Situated in an off-campus industrial park and staffed by permanent staff engineers, faculty and students, ARRI performs sponsored research and development to meet its stated mission of advancing its customers toward World Class Manufacturing.

The first approach to ASF was to develop a system to remove scalloped CNC machining artifacts from the contoured surfaces of aerospace wind tunnel models. The results of this study were used to establish the need for finishing tool compliance and active force control. An Active Force Device (AFD) was conceived, developed and patented during this program. This device is distributed by an ARRI spin off company, PushCorp, Inc. of Dallas, Texas, USA.

Subsequently, ARRI undertook the robotic polishing of aircraft fuselage and wing skins. This application reinforced the need for reverse engineering the surface to be finished, and the development of a contour surface model to support the path planning and programming functions for surface finishing. We were able to demonstrate the mechanical digitization of a target portion of the skin without hard tooling and part registration, the development of a surface model, including surface normals, and generate robot controller code to immediately start the finishing process according to a predefined path pattern. This is close to real-time automated surface finishing robot programming! The software developed at ARRI for this task is called RobSurf. RobSurf has been operationally confirmed by other industrial laboratories such as Boeing.

There are a lot of problems associated with the use of manual labor for surface finishing. First and most important are the errors and inconsistencies associated with worker's fatigue. These errors sometimes proved to be very costly due to the amount of rework that had to be performed. In the current labor market, the companies that we worked with, indicated that they are observing a shortage of skilled labor in this field due to the intensity of the process. The process itself possesses safety hazards such as cumulative trauma disorder and the exposure to the generated dust.

There is an abundance of information in the literature for reverse engineering of surfaces using various approaches that are too many to mention. In addition, a lot of research has been performed in the area of automated robot deburring with the work focusing on tooling development. It is important to mention that there are also available robotic off line programming (OLP) packages that generate native robot control code for almost all available standard robots in industry.

Off line programming packages such as Igrip by Deneb, CimStation by Adept, Rose by Tecnomatics, etc. do have process modules for various manufacturing applications such as painting, welding, and other industrial process. However, to the best of our knowledge, none of these commercial OLP packages has a surface-finishing module. The lack of a surface finishing module in industrial OLP packages led us to the development of an in house system.

A surface finishing module should be characterized by ease of expansion, modularity and open architecture for experimentation purposes. These characteristics will allow a robot user to experiment not only with process parameters but with various features of the workpiece as well, generate native robot control code for surface finishing of contoured-complex surfaces while at the same time include information about the characteristics of the process. We have developed, tested and verified such a system at ARRI called RobSurf.

3 RobSurf History

RobSurf is an open architecture surface finishing system that runs under AutoCAD. The development for RobSurf was initiated in the early 90s and at the time, it seemed appropriate to use AutoCAD as the main platform for development. The main reasons for using AutoCAD were the openness of AutoCAD as it related to interfacing with external digitizers, the ease of querying and extracting information from its database, the availability of AutoCAD since UTA is an authorized AutoCAD training center, and more important the available human expertise in programming within the system.

Initial development commenced by Dr. Adams (MS student at the time) and Mr. Fitzgerald (ARRI manager at the time). The foundations for the system were laid, and development was performed in both AutoLisp for interfacing with the AutoCAD database and C for other operations. This foundation is currently being used as the main interface between the main system and the AutoCAD database. The development continued with new features added according to the requirements and needs of sponsoring companies. Contributors to the subsequent development included the authors of this paper, Mr. Labalo, Dr. Shiakolas, and Mr. Fitzgerald until his departure from ARRI.

The open architecture environment was addressed by providing entry points to the code where users could write and interface their own modules that address specific surface finishing needs on conventional and non-conventional materials. RobSurf was envisioned as a platform for identification of process parameters through experimentation. Therefore, soft setup methodologies that allow for the quick registration of the workpiece in the finishing cell were included through the use of a digitizer.

4 Automated Surface Finishing Parameters

Surface finishing is a complex process for which the process parameters are usually determined experimentally. Therefore, an open architecture system must provide the user the options of easily changing process parameters for experimentation purposes. Since RobSurf was initially conceived to be an experimental tool, it provides the user the capability to easily change the process parameters and then automatically incorporates the changes in the generated native robot control code.

The motion process parameters that could be defined are related to the path and the area to be finished. The path related features are subdivided according to the path orientation, the pass spacing and the type of motion dithering as shown in Figure 1.

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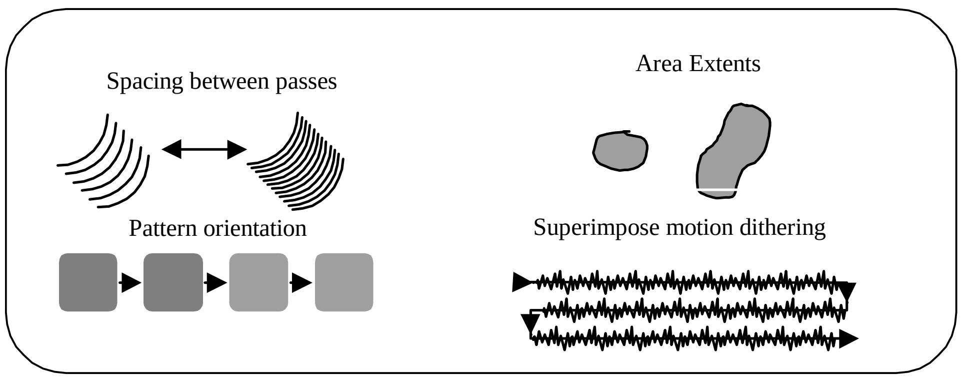


Figure 1: Path Pattern Features

Control parameters that could be defined during the programming stage are the speed of the robot, the normal applied force, and the relative orientation of the grinding tool with respect to the surface normal and path direction (cant and rake angles). Other parameters that are not defined during the programming stage include the type of the tool used for finishing, and the type of media and grit size.

5 Theory of Operation of ASF Cell

In an automated surface finishing cell which must accommodate several different workpieces, setup of the workpieces must be kept simple and quick with minimal fixturing. Two important capabilities are to be designed into the cell to achieve these goals. Soft setup capability employing CAD methodologies and measurement technology will be implemented to take the place of expensive part number specific holding and locating fixtures as shown in Figure 2.

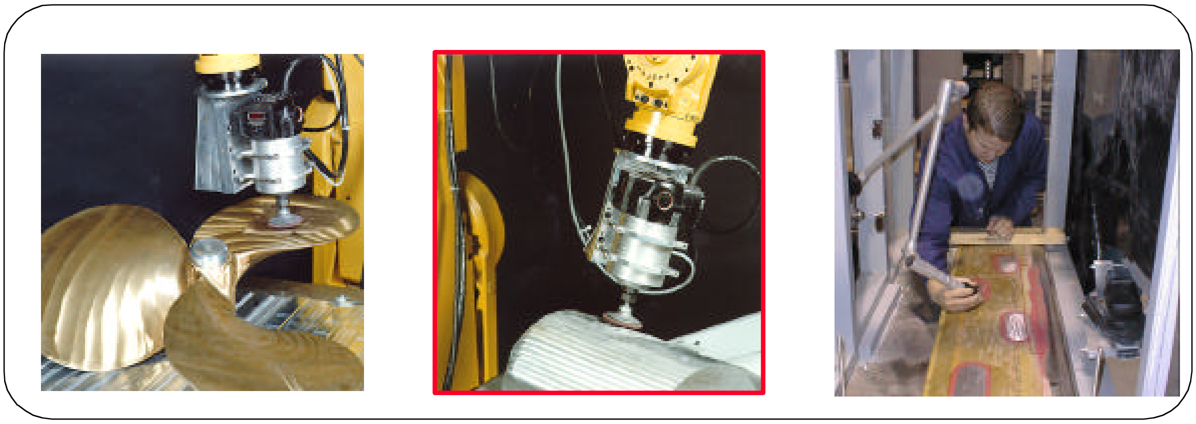


Figure 2: Some of the workpieces experimented with in the ARRI ASF cell

Operator task planning and monitoring will be employed in order to put the operator in the process control loop. The human operator will provide a task-planning interface for future adaptations and variations in feature size and location. This will ensure that these variations will not affect the process and that the robot could effectively operate on all the features.

5.1 Soft Setup for ASF Cell

Soft setup refers to the use of computerized geometric models calibrated within the robot workspace to guide the physical location and orientation of the finishing actions. The various workpieces will have limited hard tooling geometric locating capabilities. The soft setup capability is implemented in our cell through the use of a coordinate measuring device calibrated with respect to the robot tool plate as explained later and demonstrated in Figure 3.

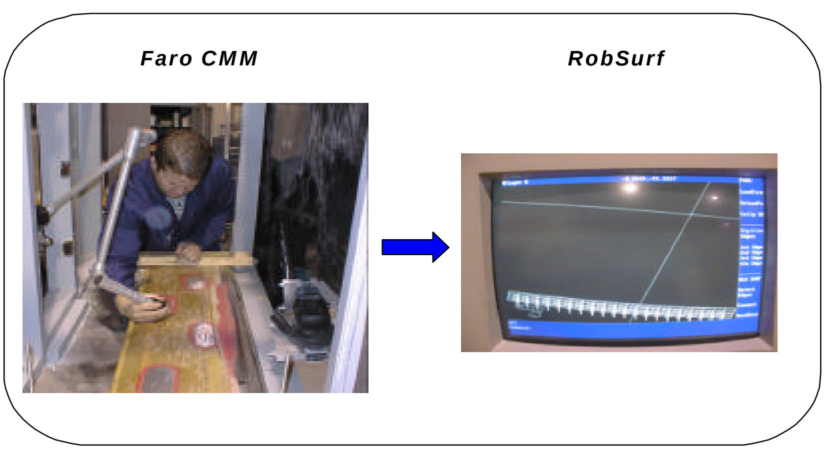


Figure 3: Digitizing process in ASF cell at ARRI

Measuring the spatial position and orientation of workpiece features relative to the robot world frame will perform soft setup. The setup functions include:

- Locate the workpiece reference frame
- Find the spatial transformation between the workpiece and robot reference frame
- Reverse engineer a computerized (CAD) surface model of the workpiece from measurements taken during setup or referenced and extracted from a master CAD model
- Locate and characterize the geometry of the features to be faired.

The choice of measurement methods will depend upon whether the surface is to be reverse engineered or whether existing CAD models will be used to “overlay” the actual workpiece. Measurement methods under consideration include:

- Manual digitizing: This is the method currently used in the ARRI lab. This could be applied in production by mounting the digitizer on the same bridge as the robot so that it could reach throughout the robot work volume. The digitizer would then be operated manually during part setup
- Robotic probe - teleoperated: This method would require the development of a teleoperated path planner that would use joystick input. Then, the robot equipped with a point measurement sensor will act as the digitizer
- Robotic probe - automatic: This method is the same as above except that an automatic scanning methodology would be developed. The robot will manipulate a non-contact sensor to scan the workpiece.

The choice of the method to be used for soft setup depends on the actual workpieces to be faired and the required accuracy and surface finish characteristics. Note that, whichever method is selected, the output of the digitizer could easily be interfaced and recorded in RobSurf. Subsequently, RobSurf will develop the robot native control code according to the user defined process parameters.

5.2 New Tool Calibration

One important aspect of an experimental setup is the ability to easily change and calibrate tools to be used during the experiments. In this section, we will describe the process with which we calibrate a new tool with respect to the robot and the digitizer. This procedure applies to the robot in the current finishing cell, a GMF S-400. However, a similar approach should be applicable to other robots.

Every new tool must be calibrated before its use in the finishing cell. This is accomplished by evaluating the $UTOOL system variable in KAREL (KAREL is the native language for the GMF robot). The $UTOOL system variable describes the position of the tool center point (TCP) relative to a coordinate system on the robot tool plate. Then, the $UTOOL variable is defined for the particular tool and stored in the RobSurf tool database. During the generation of the robot native code, the user must define the tool to be used for experimentation. Once the tool is selected, RobSurf will automatically set all the system variables for the controller for the selected tool.

The system accuracy is highly dependent on both the coordinate measuring machine calibration with respect to the robot tool plate (Figure 3) and the new tool calibration with respect to the robot tool plate (Figure 4) processes. A fixed coordinate measuring machine is used for the calibration processes. These processes calibrate not only the toolpoint to the robot tool plate but register the workpiece in the robot workspace as well.

In our surface finishing cell, we use a 6-dof FARO manual digitizer. The calibration procedure will be described for one of the tools used in the finishing cell, a forming tool. The TCP for the forming tool is located 150 mm along the positive x-axis of the flange, 60 mm along its y-axis, and 32 mm along its z-axis, with an orientation of positive 90 degrees around x-axis and positive 90 degrees around z-axis. These values are used in the defining the system variable $UTOOL. The steps for calibrating this tool in RobSurf are as follows:

- Select Caliper3d item from the FARO menu and go to <Collect 3d points option>
- Point the digitizer tip at the center of the robot tool plate and save the x, y and z coordinates (Figure 3)
- Attach the tool to be calibrated on the robot tool plate. Then, touch the digitizer tip at the TCP and save the x-, y-, z- coordinates (Figure 4)
- Calculate the offset in x-, y-, z- directions between TCP and center of the tool plate
- Determine the roll, pitch and yaw angles of the new tool coordinate system relative to the tool plate coordinate system
- To update the RobSurf tool database: Open the KAREL.LSP file using a text editor and go to the line starting with (if (= toolid "dtat" (setq toolid "-192.74,60.43…….))
- Copy this line below and define the tool name and identification number in the place of "dtat" and toolid respectively and the x-, y-, z-, roll, pitch, yaw values
- Save the KAREL.LSP file. The next time you run RobSurf, the new tool will be available for use

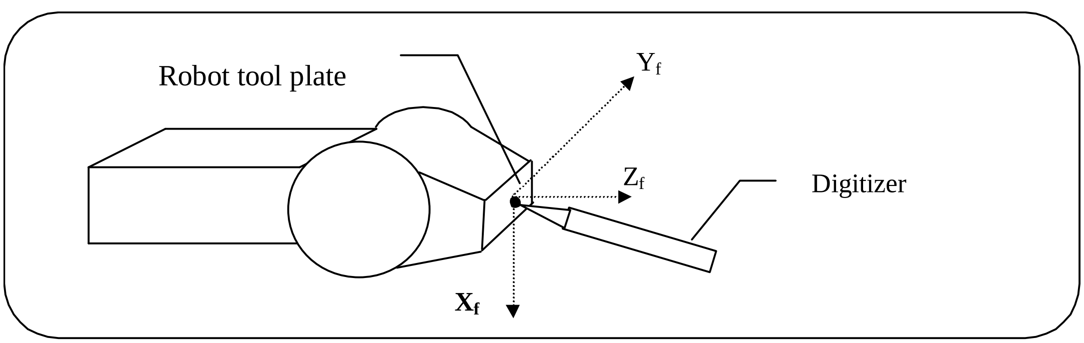


Figure 4: Measuring the robot tool plate center coordinates for CMM calibration

6 Theory of Operation of RobSurf

In this section, we will discuss the theory of operation of RobSurf and the procedure for acquiring surface model data and generating the proper information for the robot control code. Using the coordinate measuring machine interfaced with AutoCAD, the system is capable of reverse engineering a CAD model of the scanned surface and generating the KAREL code for various routines such as fairing, filling or forming. The surface-model is defined by the mesh grid with calculated frame normals on each of the nodes. The KAREL code is transferred to the GMF controller via an RS-232 connection. An active force device (AFD) is used between the robot tool plate and the actual process tools. The AFD is employed to perform the force control functions due to the difficulties and problems associated with performing through the arm force control since the proper control of the applied force is one of the main parameters of the surface finishing process. It is important to mention here that the current implementation provides for the easy generation of native control code for other industrial robots apart from GMF with minimum adaptations.

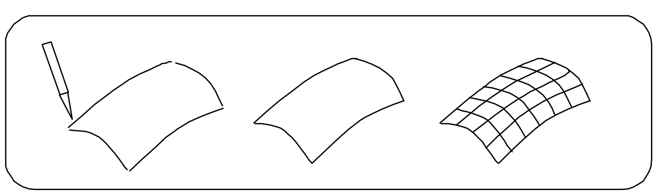
The current RobSurf system requires the following modules for proper operation. A brief description for each module and its operation is presented.

- RobSurf software
- Kfloppy software
- AutoCAD
- GMF Controller
- Coordinate measuring machine (CMM)

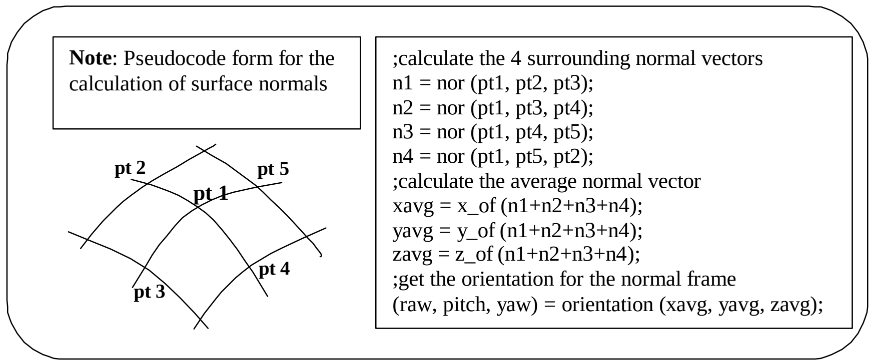
6.1 RobSurf Software

The main purpose of the RobSurf software is to acquire points from the CMM, reverse engineer a surface model and generate paths and associated normal frames. Implemented in AutoLisp, the main functions can be run from the AutoCAD command line or AutoCAD menu. The important steps from scanning the surface to getting executable code for the robot will be illustrated. Main functions and associated variables, and function calls will be described.

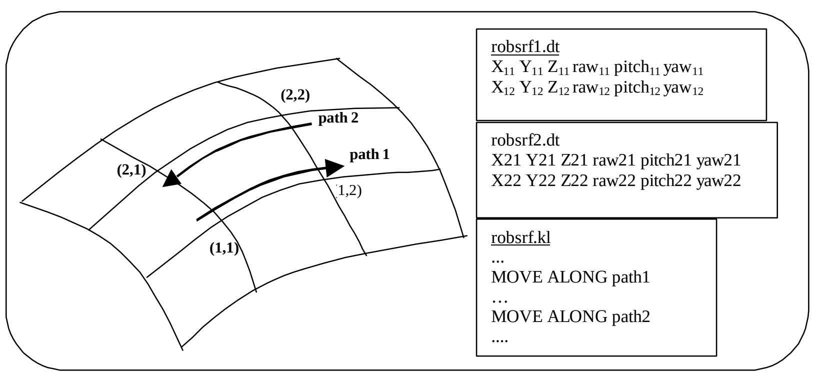
- The operator defines the variables for the desired process and runs the RobSurf function
- RobSurf calls the function for polyline scanning. This function is implemented by the FARO CMM
  Four polylines needed to be scanned
  RobSurf routine connects polylines into a surface polygon
  RobSurf calls the AutoCAD “edgesurf” function for mesh generation based on the surface polygon and the mesh density defined by the user during the initialization stage. Note that the 3D surface is treated as a 2D plane at this step (think of it as a blanket stretched over the initial 3D surface and then unfolded and analyzed as a 2D one)



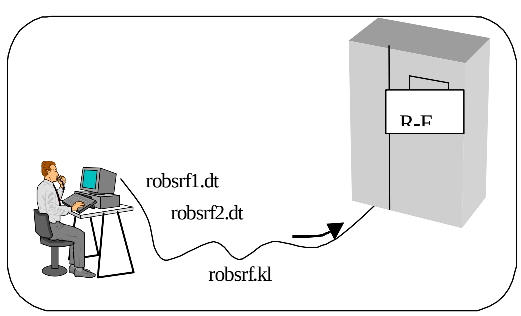
- RobSurf calculates the normal vector for each node and finds orientation for corresponding normal frame. Normals are calculated using the AutoLisp function "nor"
  Orientation is evaluated using a function implemented in RobSurf



- RobSurf generates the paths for the robot and then the robot native control code in KAREL to be transferred to the controller



- RobSurf calls the Kfloppy program (floppy disk emulator for GMF controller which interfaces between the PC and robot controller via RS 232C communication) for transferring the generated code and path files



- The operator calls the procedure from KCL prompt on R-F controller for deleting files from previous session and translating (compiling into binary executable code) the downloaded files. Upon successful completion, the downloaded code is ready for execution

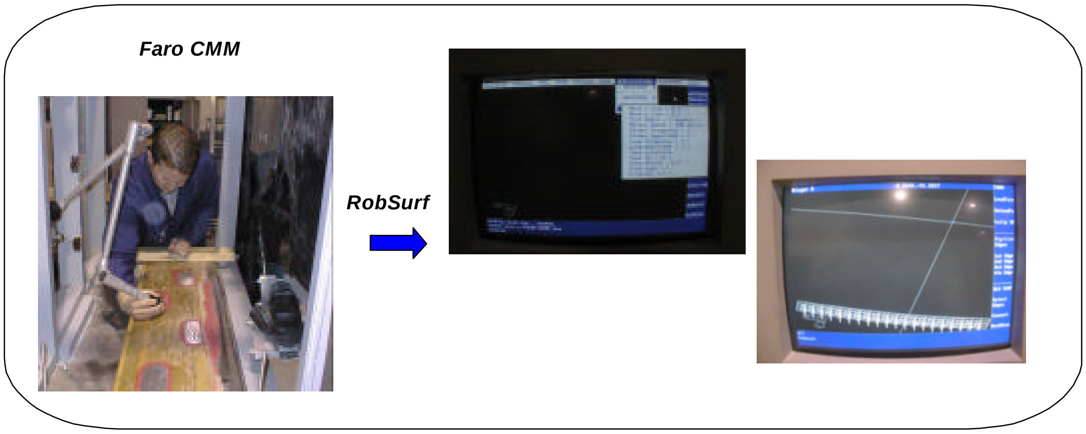


Figure 5: Operation of RobSurf system

6.2 RobSurf Parameters and Functions

RobSurf is developed mainly for experimentation. As such, it provides the user the capability to define values for process parameters/variables during execution of RobSurf. The following table gives the name, description, type and default values for the available process parameters/variables. In addition, we mention main function calls and their purpose. Details about the various calls, variables and their usage are provided in the RobSurf user's manual.

Table 1: RobSurf Process Variables

Name	Description	Type	Default
tltang	Tilt angle	degrees	3
uvar	Mesh density for u-direction	inches	0.1
vvar	Mesh density for v-direction	inches	1
speed	Robot speed	mm/sec	200
toolid	Tool identification	fc {DA sander} ff {Fill and Form tool} ffa {Fill and Form tool adapter 1} dt {Dispensing tool} dta {Dispensing tool adapter 2} dtat {Dispensing tool tilt syringe}	fc
rptpath	Number of passes		5
pthtype	Trajectory type	1 {passes in one direction} 2 {loop path}3 {dither path} 4 {zig zag path} 8 {passes in two directions}	1

6.2.1 Function: type1() {called by robsurf()}

Calculates the orientation of the normal frame for each node on the surface mesh grid by using the four surrounding nodes.

It sorts the nodes in a fashion defined by desired trajectory type, and stores them in files. Each path has its own associated file with list of points in the form of x y z roll pitch yaw.

6.2.2 Function: klf() {called by robsurf()}

Generates ASCII KAREL code which defines the number of passes, and the specific GMF system variables, $speed and $UTOOL. Robot paths are built out of robsrf*.dt data files. This is one of the functions that must be modified for implementation for other industrial robots since it defines the $UTOOL variable.

6.2.3 Command: m

Converts the points.dt file with path points from the format generated by the FARO digitizer into x y z roll pitch yaw, and then it generates the KAREL code. This is one of the functions that must be modified for implementation for other industrial robots.

6.3 Kfloppy Software

The Kfloppy software emulates a floppy disk for the R-F controller for the GMF robot. It allows one to copy files from the controller to the internal hard disk on a PC and vice-versa. The software could be executed either from DOS command or within AutoCAD.

6.4 AutoCAD

The RobSurf software is implemented in AutoLisp, a programming language integrated in AutoCAD. In order for Robsurf to properly operate some AutoCAD settings must be defined. A very important setting is “drawing limits” explained below. Other important files that must exist along with their use are also noted.

6.4.1 Drawing Limits

In order for drawings generated by the digitizer to be visible on the screen, it is important that the working volume of digitizer complies with the drawing limits in AutoCAD. The correct procedure for defining the drawing limits is the following:

- Measure the working space corners with your FARO digitizer
- Type in limits on the AutoCAD command line and put in the coordinates of upper and lower corners measured in previous step.

6.4.2 Settings in Other Files

- acad.pgp: external commands and alias definitions such as shortcuts for DOS commands

- acad.lsp: list of Lisp modules loaded upon launching AutoCAD. All RobSurf modules are listed in this file
  If a new Lisp module is generated, then this file must be updated
- surf.mnu: customized menu file with all RobSurf features. This where the RobSurf Menu items can be changed depending on the process to be performed (feature based) or tooling to be used

6.5 Coordinate Measuring Machine (CMM)

A coordinate measuring machine is used for surface scanning and end-effector calibration. Using an AutoCAD driver, polylines or simple points can be drawn directly in AutoCAD as the digitizer arm traces a part. For RobSurf purposes, the CMM generates only four polylines which define the desired area to be finished. Once the area is defined, RobSurf draws the mesh and normals.

In the following subsection some important CMM settings and the method for calibrating the CMM coordinate system are described.

6.5.1 CMM Calibration Settings

The two most important settings are Units and Stream Resolution. For the “r” function, the units are inches and a stream resolution of 0.7” should be defined. For the “m” command (generates the trajectory capturing the digitizer orientation), the units are in millimeters and the stream resolution is 10 mm. These settings can be changed by running the Caliper3d program either from the AutoCAD menu (FARO/Caliper3d) or the DOS command line.

6.5.2 Setting up the Coordinate System

The robot and CMM should reference the same world coordinate system. Setting up the CMM coordinate system highly determines the RobSurf accuracy. Several methods are available, however the most convenient one is Move Alignment with points. The set up procedure is described below.

- Set the $UTOOL system variable on the robot controller to be (0, 0, 0, 0, 0, 0)
- Move the robot to three different positions in the workspace and record x y z coordinates for each position (one can use the calib.kl program designed for this purpose)
- Run Caliper3d driver program and choose <Setup object coordinate system> item
- Choose <Move Alignment>
- Choose <Points>
- Enter the coordinates of three points recorded earlier
- Move the robot to the first point and touch the center of the robot flange with the digitizer tip
- Repeat the same procedure for the other two points.

7 Conclusions

We have discussed the development and capabilities of a tool for robotically automated surface finishing processes called RobSurf. This system has been used for identifying “optimum” fairing process parameters for metal such as brass ship propellers and non-metal such as fiberglass composite components aerospace components or workpieces.

One of the important features of the RobSurf system is the capability to generate native robot control code similar to commercial OLP packages. Unlike commercial OLP packages, RobSurf generates specifically control code that includes information about all the required parameters for surface finishing.

Another important element of RobSurf is that the system employs a fixed coordinate measuring machine that provides the capability for soft setup without the requirement of hard tooling and registration fixturing in the workcell. Soft tooling methodologies should be integral parts of any surface finishing cell and more important of experimental robotic cells.

Even though these workpieces have considerable variations in material characteristics, size and geometry, the developed system was successfully employed with changes relating only to the type and calibration of the tooling and updates to the definition of process variables relating to the specific fairing process parameters. These changes were easily included in the database of the RobSurf system. The numerous experiments performed validated the modular, expandable and open architecture nature of the complete automated surface finishing system.

This system has been operational and used in various sponsored projects at ARRI with great success in experimentally identifying process parameters for the various materials and processes examined.

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