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Application of photogrammetry to automated finishing operations

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Abstract. Buffing is usually the last and most important operation carried out during manufacturing processes, especially for use in applications that require strict tolerances. For objects with irregular geometry, this operation may have to be done manually. In an effort to automate the buffing process, robot simulation platforms can develop offline programs for specific geometries that are known beforehand. However, in the case of unknown geometries, it is required to first develop the CAD model before processing within simulation platforms. This can be done using either manual measurement of the object, which could be tedious, 3D scanning the object, which requires specialized expensive equipment, or the process of photogrammetry, which is cheap and readily accessible. This paper describes the use of photogrammetry to develop scale 3D models of irregular objects, which is subsequently used to generate tool paths for an industrial robot via offline programming, to be applied in finishing operations. The photogrammetry procedure involves compiling photographs of the target object from a 360º orientation, and using a photogrammetry software to generate the 3D model of the target object. This model is then used within the simulation software to develop the final output. A commercial photogrammetry software, Bentley’s ContextCapture, is used to develop the 3D models, which are then imported to RobotStudio which can generate end-effector toolpaths for buffing operations to be carried out on the scanned object, based on the contours of the model. The offline program thus obtained is to be transferred to an IRB 1410 6 DOF industrial manipulator for execution and verification.

1. Introduction

1.1 Overview of Industrial Finishing Operations

As technology advances, various industries are faced with a requirement to change the way they operate in order to survive, grow and optimize their current practices in order to keep up with demand and the growth of the market.

In the manufacturing industry, large scale changes are occurring rapidly in the standards used in order to remain competitive and maintain product quality standards. In the field of finishing operations like buffing and polishing, both small and large scale industries are continuously upgrading their finishing operations and facilities. The manual finishing methods used in the industry are undesirable and inefficient when planning for future goals and production projections. The availability of skilled labor for these manual operations is declining as they are not interested in working in “dirty”
manufacturing departments due to more enticing job prospects. In addition, new environmental standards limits the use of manual labor in hand grinding and deburring operations due to concern for worker health.

There is an increasing desire in manufacturing industries to replace hand-finishing operations as well as older generation machines used for the process. One option being used by several companies is outsourcing labor to off-shore companies with more readily available skilled labor.

However, this is not a viable long term solution due to costs incurred with shipping, quality standard management and lack of product control during the manufacturing process.

In response to the challenges faced in the industry, various robotic and programmable controlled finishing systems have been developed. They are designed to address several of the major factors that are considered by modern manufacturing industries, including machine flexibility, better quality of finish, reduced operating costs, improved worker safety, minimized part handling. Various existing manual operations are being converted to robotic finishing methods, which results in the reduction of manual fatigue factor and greatly reduced processing times for products. This in turn leads to a cost effective system [1].

A classic benchmark robotic application of finishing operations is the robotic work cell developed by Acme Manufacturing Co. for grinding, polishing and buffing knee implant prostheses. These work cells can combine material removal, contouring and tolerancing, and super-finishing of implants using very advanced finishing technology [2].

To summarize, as market standards evolve to push manufacturing and finishing requirements to higher levels, changes in mechanical finishing for cosmetic and functional products are implemented using robotic and computer controlled processes. Companies across the world are pushing for continuous improvement in order to grow and hold on to their market positions. As robotic technology advances, these changes will occur at an accelerated rate [3] [4].

1.2 Overview of Photogrammetry

Photogrammetry is considered one of the best surveying methods to acquire tridimensional data without direct contact with the scanned object. With the advancements in digital photogrammetry, the costs of computer hardware, cameras and the software required have decreased, making it more accessible to various fields. Photogrammetry is used for various purposes in architecture, archaeology and health fields [5] [6] [7]. Very few current manufacturing processes include photogrammetry within their work flow, and this is a utility that can be explored to improve operational flexibility.
Digital photogrammetry is a non-contact measurement system that uses a sequence of images obtained using high resolution cameras, in order to identify unique features, points and coordinates on the surface of objects. As shown in figure 3, this technique is used to map points on object surfaces.

![Figure 3. Representation of stereo-photogrammetry technique demonstrating triangulation](image)

The shape and position of an object are obtained by reconstructing for each image, the rays that define its spatial direction to a corresponding point on the object. If the imaging geometry within the camera and the location of the imaging system with respect to the object are known, each ray can be defined within the 3D object space [6]. This process is visualized in figure 4.

![Figure 4. Principle of photogrammetric measurement](image)
The advent of digital photogrammetry has drastically improved the scope and application of the process to various systems. By using appropriately targeted points on an object, along with digital image capture and recording, complex photogrammetric tasks can be completed within mere minutes, depending on the complexity of the computer hardware and software used. This high degree of automation means even non-experts can carry out process tasks [8].

**Figure 5.** Digital photogrammetric system representation

Within the photogrammetric process, several principal procedures take place over several layers. Within the recording layer, the target is selected to improve automation and accuracy of target measurement. Control points are determined to create a global object coordinate system. Digital image processing is carried out to assist in these tasks. In the pre-processing layer, computations of the reference point coordinates are carried out and these results can then be used to convert or store them as required. The orientation layer identifies and measures the reference and scale points, which are then used to calculate approximate starting values of unknown quantities. Bundle adjustment is used to determine interior and exterior parameters and finally, gross errors are detected and removed automatically. The final measurement and analysis layer creates the 3D object point coordinates and produces scaled maps which can be used for further processing [7].

In summary, digital photogrammetry provides a self-contained, high processing rate system that can be largely automated from capture to presentation of results in order to obtain object dimensions readily. The two major types are offline photogrammetry, which involves a single camera and the result is obtained after processing all obtained images, and online photogrammetry, which uses two or more cameras and can provide instantaneous and real time results.
1.3 Industrial Usages of Photogrammetry

Currently, photogrammetric techniques are used in several industrial applications including power and industrial plant stations, aircraft and space industries, car industries and ship building industries. In power plants, photogrammetry is used to generate 3D models of old pipework, for which CAD models do not exist due to age of the installation. Aircraft and space industries use the process for measurements of parabolic antennas, tooling jigs, mechanical gauges and to conduct simulations of space operations. In the car industry, photogrammetry is used to align production cells, carry out surface measurements of parts, safety tests, part inspection and obtain deformation measurements. Ship building industries use the advantage of photogrammetry in large scale environments to measure very large objects (>30m) as well as restrictive areas within the fuselage, and visualize vibrations and other external conditions.

The application of photogrammetry is limited in the manufacturing field, but advances have been made within the field of rapid prototyping, which uses photogrammetry to generate 3D models of small scale objects, which are then used to fabricate cheap replicas on a large scale using industrial 3D printers. This procedure can be expanded to utilize the obtained 3D models for a variety of further operations not limited to fabrication alone. One such application is the possibility of improving flexibility of automated finishing operations [9] [10].

1.4 Application of Photogrammetry

Photogrammetry offers several advantages to robotic finishing processes due to the decentralized nature of the process and the ease of accessibility it affords to even non-expert personnel. The output from photogrammetric operations can be used to verify surface tolerances upon evaluation within a commercial software. It can also be used for rapid fabrication and replication processes that can be quickly set up and operated, such as 3D printing operations. With a known 3D model of any target object, a wide range of manufacturing processes can be undertaken [11].

2. Methodology

2.1 Summary of Workflow

The proposed workflow for the task of automated finishing operations using outputs from photogrammetry is defined in this chapter.

The first step is to determine which commercially available software is to be used to carry out the photogrammetry procedure for the start of the process. Autodesk ReMake and Bentley’s ContextCapture software’s were selected for evaluation. Upon comparison of the results from both software using a common scanned object, the better option is selected for further usage. Subsequently, this software is used to generate 3D models of test objects of known geometries and verified via comparison to the CAD models used to generate them. These 3D models are then imported to RobotStudio to simulate the robot work cell of the final process. The IRB 1410 model robotic manipulator will be used for development of this simulation, during which the buffing tool path is generated using tools available within the software. The final step is to export the generated program within the simulation onto the IRB 1410 and execute it in real time on the test objects after which the results of the finishing operation will be compared to those obtained by manual methods.
2.2 Details of Working Approach

2.2.1 Image capture

The procedure for capturing the images is very important and plays a major role in the output of the photogrammetry process. Images need to be taken in a 360° arc around the object, evenly spaced,
and with at least 50% image content overlap compared to the prior image. This will ensure that the software used will have the appropriate number of data points in order to perform the triangulation process correctly.

Moreover, the object must not be reflective, transparent or translucent. Reflective surfaces will introduce contextual errors within the software’s, making a closed mesh output impossible. Translucent and transparent surfaces will not be reliably recognized by the software, again leading to mesh errors.

In order to accurately scan objects with these surface properties, it is necessary to temporarily treat the surface of the object so as to compensate for them. Chalk paint or talcum powder can be used to render a matte finish on the object, and diffuse white light must be used to avoid shadows on parts of the contours.

2.2.2 Photogrammetry software

The acquired sequence of images is fed to the respective software being used. Autodesk ReMake uses cloud computation technology to process the images, which involves uploading the images to a cloud drive at which point, the Autodesk service works on them remotely. Conversely, Bentley’s ContextCapture uses local system resources to perform the photogrammetric task.

2.2.3 Comparison of results

The result of the procedure from both software’s is compared to decide which of the two provides a more robust and detailed 3D mesh, with fewer errors and complications. Moreover, the level of setting customization available to the user during the setup for photogrammetry is also considered. A greater amount of flexibility is required so as to operate on photographs with a wider range of properties such as lighting, background, colour distribution, etc.

Upon acquisition of a closed 3D model from each software for the same test object, the meshes are compared with the above requirements in mind, and the better option is selected for further use throughout the project.

2.2.4 Scanning of test geometries

Upon selection of the appropriate software to carry out photogrammetric tasks, a test geometry must be fabricated, in order to be used as the base structure that will undergo testing both within the simulation software, as well as in real time execution of the polishing process.

The test geometry is designed with a CAD package and fabricated with a 3D printer for scanning and testing using the selected photogrammetry software. The use of 3D printing allows for multiple test geometries to be tested at a higher rate than if traditional metal stock was used to fabricate the required objects. This leads to a larger variety of results in a comparatively shorter period of time.

2.2.5 Importing generated 3D models to RobotStudio

Once the fabricated test geometries have been scanned and converted to 3D models by the software, they are exported as STL files to be used by the simulation software RobotStudio. It must be ensured that the STL files are of ASCII type and not binary, in order to avoid import errors within the software.

The generated STL files are imported to RobotStudio individually as station components. A single geometry is used for each simulation test. The IRB 1410 robot manipulator is setup within RobotStudio and the test geometry is oriented with respect to the workstation as intended to be used in real time.

2.2.6 Generation of tool path

Once the simulated work space has been initialized, the tool path for the IRB 1410’s end effector can be generated using the in-built Auto Path function available in RobotStudio. The target surface on the model of the test geometry is selected, and the software automatically calculates the tool
path required for the specified operation, along with all the relevant motion parameters. The required cycle time analysis is also carried out to provide an idea about the time required to complete the operation.

2.2.7 Execution of generated tool path
The tool path for the end effector obtained within the simulation is ready to be verified in real-time operation on the IRB 1410 manipulator. The generated program is exported to the robot controller and the robot work space is setup exactly as it was initialized within the software. After ensuring the robot has been properly calibrated, the program is executed to verify. The entire operation is timed, from start to finish to establish the rate at which each object is polished using the robotic manipulator.

2.2.8 Manual polishing of test geometry
In addition to the automated polishing procedure, a copy of the same test geometry being used needs to be manually polished, so as to provide a control result that can be used to compare with the output of the automated procedure. The manual polishing is carried out using standard techniques as used in industry. Each polishing operation is timed to provide data for future comparison.

2.2.9 Comparative study of surface finish
Once both test geometries have been polished by their respective methods, their surface qualities are tested, the area roughness parameters of several points on the surface is measured so as to compare their outputs. These results are replicated with multiple test geometries so as to provide a wider range of data, using which a conclusion can be derived. Several factors need to be considered when making the comparison, including measured surface roughness, polishing coverage, and time of operation.

2.2.10 Conclusion of comparative study
Based on the measured surface roughness parameters of both objects, a conclusion is drawn between the results in order to determine whether or not the automated polishing procedure provides a better result, and also whether there are limitations to the automated polishing procedure as compared to the manual procedure.

3. Results and Discussion

3.1 Software Testing
The first step of work involved testing the photogrammetry software listed to be used in the project in order to determine the optimum photography procedure to acquire relevant images, as well as to compare the performance of the two software being considered, namely Autodesk ReMake and Bentley’s ContextCapture.

The first tests resulted in unusable meshes due to inaccuracies in the photography technique. This procedure was iteratively refined using different target objects and tested with both software to verify the output. The final successful result was obtained using a generic vase as the test object. Upon comparison of the output of both software, Bentley’s ContextCapture was determined to be the more precise and robust utility for the purposes of this study and hence, selected for future work.
As seen above in the output obtained for the third and final photogrammetric test, both softwares were able to generate a complete and detailed mesh of the ceramic vase used as the test object. The combination of appropriate lighting, combined with the non-reflective and well defined surface finish allowed for a more accurate result.

When photographing objects that do not share these properties, it is necessary to artificially imbue these qualities on them for the duration of the photography process. One such method that could be applied when capturing images of reflective or glossy surfaces is to spray the surface with chalk paint. This substance is non-permanent, and upon application of a uniform coating, renders surfaces with the same superficial properties as a ceramic surface similar to the above vase.

### 3.2 Model Calculations

For the final test, four primary sequences of images were taken in a 360° arc around the target object and additional images along the vertical axis were added to complete the full surface capture. This set of images was input to the software, which then computed the 3D model locally using system resources. In figure 10, the representation of all the camera positions used during the photography process is obtained using stereo-photogrammetry which triangulates backwards each position.
Of the four primary image sequences, the inner two were taken with the camera at a distance of 10 cm from the vase with 9 and 13 images respectively for the top and bottom sequences, while the outer two sequences were taken with the camera at a distance of 25-30 cm from the vase with 11 and 13 images respectively for the top and bottom sequences. A total of 58 images was used for this process.

In figure 11, the obtained 3D model is used to calculate the various measurements of the test object using the utilities built into the Acute 3D Viewer. This result is displayed in terms of generic units, which can then be used to develop a custom scale of the object as required for any operation. A list of the measured values is displayed in table 1.

![Figure 10. Representation of camera positions for each image, with respect to test object](image.png)
From the results, it can be concluded that the above procedure can be used to evaluate the geometries and surface representation of the desired objects, provided the image acquisition techniques are correctly carried out. The peripheral tolerances can be known, which are important inputs to the robot for future polishing operations.
Figure 13. Graph indicating scaling factor variation with Diameter in height and maximum diameter

2.41
2.37
2.34

SCALING FACTOR

- Top diameter 9.95 units 24 cm
- Max diameter 11.96 units 28 cm
- Height 21.35 units 50.5 cm

Figure 14. Graph indicating the variation of X, Y, and Z co-ordinates of each camera position with respect to global origin for a complete image capture sequence.
4. Conclusion and Future Work

With the successful generation of the 3D model using ContextCapture, the task of implementing photogrammetry has been addressed. In the future, the software will be used to obtain the 3D model of test objects fabricated specifically for the use of the project. These 3D models will then be exported as STL files which are then imported to RobotStudio for further operations including simulation of the polishing process, and calculation of the cycle time.

Within RobotStudio, the imported model can be defined as an object within the simulated work space, and path generation tools will be used to simulate a machining tool path for the simulated IRB 1410 robot manipulator.

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