THERMAL SPRAYING ROBOT KINEMATICS AND LASER PATTERN CONTROL

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Abstract: The thermal spraying surface engineering industry relies on manual spraying and standard pre-programmed robotic systems. This research presents the completed geometric forward and inverse kinematics solution for a non standard articulated robotic manipulator which includes continuous 360^0 axis rotation for waist, shoulder and elbow joints with a commercially available joint for tilt and pitch. The research also details the use of Polytetrafluoroethylene (PTFE) electroless nickel slip rings and brushes for providing delivery of power and data through the continuous rotation joints. The automatic analysis of distance and orientation measurement via a pattern producing laser and camera system is being researched for suitability in the thermal spraying process for automatic feedback and control of the robotic arm manipulator. The competed technical and simulation design will provide for the automatic application of advanced surface coatings to enhance wear, low friction and corrosion resistance properties to substrates via a thermal spraying process.

1 THERMAL SPRAYING SURFACE COATING

1.1 Introduction

Surface coating via thermal spraying involves the application of wear and corrosion resistant coatings to various substrates and has been traditionally carried out in the aerospace, power generation and petrochemical industries (Air Products). However improvements in the technology has resulted in opening up of additional markets, in particular in the biomedical and electronic coating industries. It is further possible today to apply coatings to polymer-based materials (England). Thermal spraying is a generic term for a range of thermal spraying technologies. There are four systems. These consist of High Velocity Oxyfuel Spraying (HVOF), Plasma spraying, Arc spraying and Flame spraying. Flame spraying for example is used in the application of corrosion resistance aluminium to off-shore oilrigs (Air Products, Richard Halldern) Another example of surface coating is biocompatible hydroxylapatite coating of prostheses, which are made of materials such as titanium. This is achieved with the HVOF system.

1.2 Powder Flame Spraying

The majority of components are sprayed manually or via standard pre-programmed robot manipulators and the development of an autonomous robot arm to carry out the thermal spraying process will reduce costs and health and safety risks.

A schematic of the powder thermal-spraying process is shown in Figure 1.

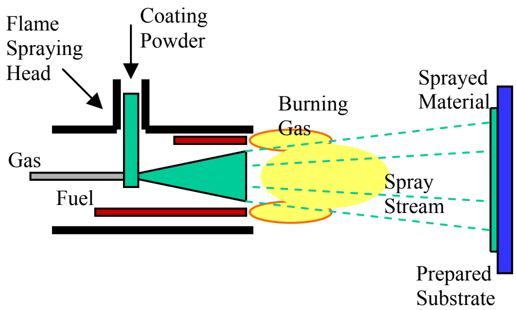

Figure 1: Powder thermal-spraying process

The coating process must occur in a very precise manor to ensure quality control. Following surface preparation, there can be up to three main stages in applying a metallic coating to a substrate and control of the position of the torch at each stage is an important design and control parameter.

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The three stages are pre-heating the substrate, spraying the substrate with the coating material and finally fusing the coating to the substrate. Other processes only require pre treatment by shot blasting. The coating and fusion process takes place in a single step such as plasma or HVOF spraying.

2 ROBOT ARM KINEMATICS

2.1 Model of a five-axis articulated robot arm with 360^0 joints.

While researching the type of robot manipulator applicable to thermal spraying it became clear the articulated type was preferable. It was also decided to include the novel feature of continuous 360^0 rotation for the waist, shoulder and elbow joints which provides advantages of maximising workspace and improved flexibility. A 5 DOF manipulator will also be specified, as spraying does not require a roll axis thus reducing the cost of additional joint actuator and control equipment.

The model of a five-axis articulated robot arm design, which has continuous 360^0 rotation waist, θ_1 shoulder, θ_2 and elbow, θ_3 joints is shown in Figure 2. A commercially available Omni-Wrist unit will provide the pitch and yaw axis joints available from Ross-Himes Designs. [Joints in grey, links in black].

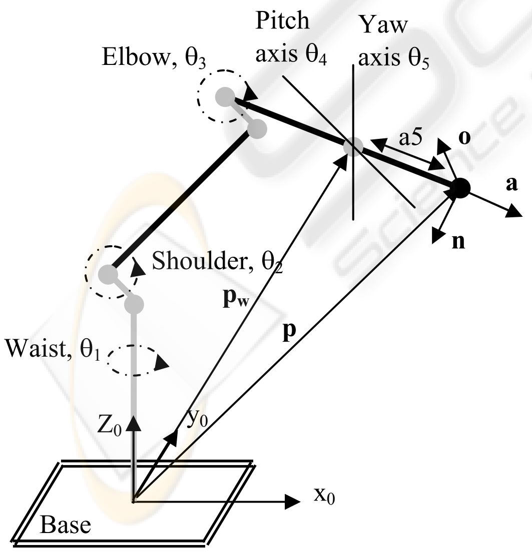

Figure 2: Five axis robot arm model

2.2 Forward Kinematics

Using the Denavit and Hartenberg (Niku, 2000 et al.) method and standard notation for developing the robots forward kinematic arm matrix, $^{R}T_{H}$ produces a set of highly coupled, non linear equations in θ_1, θ_2 , θ_3, θ_4, and θ_5 for this particular robot design. The Matlab™ symbolic toolbox was used to produce the equations. To test these equations a model of the robot arm was made using Lego™ and sample solutions were tested successfully against the physical model. As an example, using the vector of angles in degrees [-170 50 –45 20 –30] produces the position and orientation matrix

n	**o**	**a**	**p**
-0.42	-0.30	-0.86	3.46
-0.07	-0.93	0.36	-7.45
-0.91	0.21	0.37	24.56
0	0	0	1.00

2.3 Inverse Kinematics

To solve the inverse kinematics for this robot arm with 360^0 continuous rotation joints the techniques detailed in Sciavicco and Siciliano, 2000 and Niku, 2001 have been combined and modified as necessary. The steps necessary to solve the inverse kinematics are now detailed.

Step 1: From Figure 2 the wrist position vector is given by $\mathbf{p}_w = \mathbf{p} - a_5\mathbf{a}$.

Step 2: The second step is to determine the waist angle θ_1. This can be obtained by considering the plan view of a general position angle θ_1 shown in Figure 3.

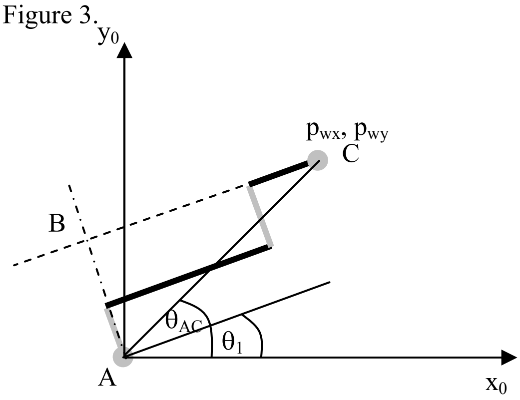

Figure 3: Plan view at angle θ_1

The angle |AC| makes with the x_0 axis can be determined from $\theta_{AC} = \mathrm{Atan2}(p_{wy}, p_{wx})$. The length $|AB| = d_2 + d_3$ (fixed quantities) therefore $\angle BAC$ can be determined from trigonometry. The angle |AB|

makes with the x_0 axis is $\angle BAC + \theta_{AC}$ therefore $\theta_1 = \angle BAC + \theta_{AC} - 90$ degrees. The angle θ_1 for any point on the circle scribed by |AC| can be obtained with this technique as can the angle on any plan view circle within the robot arms workspace.

Step 3: Once θ_1 is determined the solution for angles θ_2 and θ_3 become solutions for a simple two axis robot arm in two dimensions as long as the p_{wx} component is the length |BC| shown in Figure 3.

Step 4: Now that the waist, shoulder and elbow joint angles have been identified a change of approach will provide solutions for the pitch and tilt angles. The forward arm matrix is made up of the multiplication of six translation and rotation matrices

$$^{R}T_H = A_1A_2A_3A_4A_5A_6$$

The product $A_1A_2A_3$ and its inverse can now be calculated, therefore multiplying the given position and orientation matrix by the inverse of $A_1A_2A_3$ will provide a pan_tilt matrix, which is equal to $A_4A_5A_6$. A_6 is a constant known rotation and inspection of the coefficients of $A_4A_5A_6$ provides solution equations for θ_4 and θ_5 which are:

θ_4 = Atan2(pan_tilt(1,1), -1*pan_tilt(2,1))
θ_5 = Atan2(-1*pan_tilt(3,3),-1*pan_tilt(3,2)).

The solution outlined does not make use of the 360^0 continuous rotation capability of shoulder and elbow joints as solutions will always place these angles in the right half circle whose centre line is along |AB| and containing the point C. However if the shoulder and elbow joints make angles which move point C into the opposite half of the circle then a simple change will produce the alternative solution; $\theta_1 = \theta_{AC} - \angle BAC - 90$. The p_{wx} component will be negative for this condition.

In a practical application requiring random movement to different locations both solutions could be tested and the one requiring the shorter travel distance would be executed. The solution complying with pitch and tilt limits also requires testing, as does the elbow up and down options.

A Matlab^{TM} function `inv_axis_5.m` has been written which implements each of the steps outlined for the first solution. However data to test the code is difficult to generate. The data must be within the operational workspace of the robot manipulator and not cause singularities. Most robot manipulators are pre-programmed and components to be sprayed must be placed in exact location and orientation, which is very time consuming. This highlights one of the key areas for more advanced research, that is the generation of trajectory data using information from 3D transducers for the robot to operate autonomously and to carry out requested random movements efficiently. To test the code the forward kinematic function `axis_5.m` was used to generate position and orientation data as input data to the inverse kinematics function.

Running the function using the previous numerical example in section 2.2 where the input angles are [-170 50 –45 20 –30] provides solution angles which are different [-170 20.7 45 -40.7 –30] but with identical input and output position and orientation arm matrices, highlighting the different solutions outlined. The tilt and pan angles are within range.

A significant advantage of continuous rotation 360^0 joints is the travel distance/time required. As an example if the robot arm is in the home position and a call is made for the shoulder joint to rotate 260^0 the robot can move in the opposite direction by -100^0 in a shorter time. If the same time is acceptable the robot can move slower with less vibration. Safety is a key issue and must be taken into consideration with 360^0 continuous rotation calls as the torch may hit the vertical joint.

Determining closed form inverse equations produces a more computer efficient system than alternative methods, which use the forward kinematic equations, and iterative methods such as Gaussian elimination (Niku).

2.4 Joint cabling

Joint cabling research for power and data is pointing to the use of PTFE electroless nickel slip rings and brushes. PTFE electroles nickel has the advantages of low coefficient of friction, low wear and being a good conductor. A prototype slip ring and brushes test rig using electroless nickel coated copper samples was set up and zero resistance was recorded on the lowest resistance setting (200 Ω) of a standard digital multimeter. Inclined plane tests indicate a coefficient of friction for electroless nickel on electroless nickel, which is 30% better than copper on copper. PTFE electroless nickel should provide better results than this. The slip ring and brushes was videoed with the video signal passing through the slip rings without any appreciable reduction in quality.

3 LASER PATTERN CONTROL

Research is now concentrating on mapping autonomously, complex 3D surfaces in the harsh environment of thermal spraying, for autonomous robot manipulator control. This will reduce pre-programming and set up times significantly.

Initial depth measurement tests have been carried out on the steel plate shown in Figure 4 with a web camera and presentation laser. Image processing and analysis has been carried out using NeatVision (Whelan and Molloy, 2001), an open source Java based image processing software package and Matlab^{TM} Image Processing Toolbox. Figure 5 shows two white dots clearly separated, correlating to the raising of the plate.

Further work on applying this technique and measurement resolution obtainable in the harsh environment of thermal spraying applications shown in Figure 6 is ongoing.

Figure 4: Steel plate

Figure 5: Depth

Figure 6: Harsh Thermal Spraying environment

Further research will also consider the use of patterns produced by a laser when passed through a diffraction grating for 3D surface mapping. As an example the patterns shown in Figures 7 and 8, provide information on depth (size of circle), flat surface angle (elongation of circle) and sharp edges (discontinuity of the circle).

Figure 7: Circle and Elongation

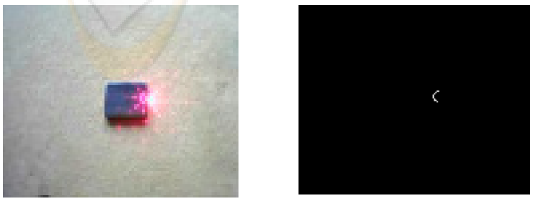

Figure 8: Discontinuity

Applying image subtraction tresholding erosion dilation and thinning provides black and white outline images of the circle, oval and semicircle for further analysis. Image processing values were chosen manually and the intended aim of the research is for these values to be determined automatically in the thermal spraying environment.

4 CONCLUSION

This paper has presented the forward and inverse kinematics solution for an unusual 5-axis articulated robot manipulator with 360^0 continuous rotation of the waist, shoulder and elbow joints, and providing an efficient method for determine joint angles from given tool tip position and orientation. The advantages of such a manipulator are also presented. The paper has outlined the progress on developing an efficient slip rings and brushes solution for cabling through the continuous rotation joints.

The paper has also highlighted techniques being pursued, which will be researched for their effectiveness in the harsh environment of thermal spraying. Solutions will transform time-consuming pre-programmed thermal spraying operations to an efficient autonomous operation.

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