

**COLLOSION AVOIDANCE AND TOOL PATH ADAPATION FOR
MULTI-AXIS ROBOT IN PLASMA SPRAY COATING PROCESS**



E076480

NATTAPON AROONCHOTE



เลขหมู่.....
เลขทะเบียน..... **76480**
วัน,เดือน,ปี..... **25 อ.ค. 2557**

b. 25 2557
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**A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF
MASTER OF SCIENCE IN AUTOMOTIVE ENGINEERING
(INTERNATIONAL PROGRAM) INTERNATIONAL COLLEGE
KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG
2012
KMITL-2012-IC-M-004-020**



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หุ่นยนต์แบบหลายแกนในกระบวนการพันเคลือบด้วยเปลวพลาสมา
นักศึกษา นายณัฐพล อรุณโชติ
รหัสนักศึกษา 51061904
ปริญญา วิศวกรรมศาสตรมหาบัณฑิต (วศ.ม.)
สาขาวิชา วิศวกรรมยานยนต์
พ.ศ. 2554
อาจารย์ผู้ควบคุมวิทยานิพนธ์ ผศ.ดร. ณัฐวุฒิ เดิไปวา
ดร. นิรุตต์ นาคสุข
Prof. Dr. Hiroshi Yamaura

บทคัดย่อ

กระบวนการเคลือบด้วยพลาสมาสเปรย์ด้านในสำหรับท่อหลายส่วนรูปทรงต่างๆ ซึ่งได้มีการนำสถานีหุ่นยนต์หลายแกนมาประยุกต์ใช้ในการทำงานนี้ เป็นยากที่จะสร้างเส้นทางรถเคลื่อนที่ที่จะไม่เกิดการชนกันระหว่างหุ่นยนต์และชิ้นงานที่ทำการพันเคลือบ โปรแกรมคอมพิวเตอร์ทางด้านหุ่นยนต์จึงเป็นประโยชน์อย่างมากในการสร้างเส้นทางรถเคลื่อนที่ โดยที่ให้เปลวพ่นตั้งฉากกับพื้นผิวที่ทำการพันเคลือบและมีระยะห่างในการพันที่เหมาะสม จากแบบชิ้นงานสามมิติ แต่ด้วยข้อจำกัดของขนาดและรูปร่างของปืนพ่นและตัวชิ้นงาน จึงทำให้เกิดการชนขึ้นในบางตำแหน่งบนเส้นทางรถเคลื่อนที่ การปะทะกันระหว่างหุ่นยนต์และชิ้นงานหรือชิ้นส่วนใดๆ ของระบบนั้นจะยอมให้เกิดขึ้นไม่ได้โดยเด็ดขาด ดังนั้นวิทยานิพนธ์ฉบับนี้จึงศึกษากระบวนการป้องกันการปะทะกัน เพื่อตรวจหาคำแนะนำการพันบนเส้นทางรถเคลื่อนที่ที่ทำให้เกิดการปะทะกัน และหาวิธีการปรับเส้นทางรถเคลื่อนที่เพื่อที่จะแก้ไขตำแหน่งการพันเพื่อหลบไม่ให้เกิดการปะทะกันเกิดขึ้น นอกจากนี้ยังจะต้องสามารถรักษาเงื่อนไขต่างๆ ในการพันเพื่อให้ได้ผิวเคลือบที่ดีอีกด้วย

Thesis Title: Collision Avoidance and Tool Path Adaptation for Multi-axis Robot in Plasma Spray Coating Process

Student: Mr. Nattapon Aroonchote

Student ID: 51061904

Degree: Master of Engineering

Program: Automotive Engineering (International Program)

Year: 2011

Thesis Advisor: Asst. Prof. Dr. Nattawoot Depaiwa
Dr. Nirut Naksuk
Prof. Dr. Hiroshi Yamaura

ABSTRACT

The plasma sprays internal coating process for multi-section shapes tubular this applied by multi-axis robot station, is difficult to generate collision-free tool path manually. Robotic software is very helpful to create tool path which plasma flame perpendicular to the coating surface and adequate spraying distance, from 3D CAD model. However, the constraints of both shape and size of spray gun and the tubular cause the collision to occur in certain positions on the motion path. The collision between the tubular with robotic parts or any part of the system is strictly prohibited. Therefore, this thesis studies on collision protection system to detect spaying point on tool path which the cause of collision and find tool path adaptation algorithm in order to automatically modify that spaying point to flee from collision. Moreover, the application also retains spraying condition to keep the coating surface good as well.

ACKNOWLEDGEMENT

This thesis could not be completed without the assistance of many persons to whom I would like to express my sincere appreciation.

First, I would like to sincerely thank my advisor, Dr. Nirut Naksuk, who has given me many helpful suggestions, useful advice and fruitful discussions during the undertaken research.

I would also like to sincerely thank Asst. Prof. Dr. Nattawoet Depaiwa for kind advising and helping, and Prof. Dr. Hiroshi Yamaura for the suggestion of Robotic.

Moreover, I would like to acknowledge the Electricity Generating Authority of Thailand, for supporting a research grant. I would like to show gratitude to National Metal and Materials Technology Center (MTEC), especially the Automation laboratory for providing the laboratory equipment and instruments as well as financial supporting.

I am grateful to National Science and Technology Development Agency (NSTDA), which provided the full scholarship for studying in the master program.

Special thanks to MTEC Automation laboratory's members for helping me during the experiment, and my English teacher, Miss Pailin Pinitkwamdee, for various suggestions.

Finally, I am very grateful to my family for all love, caring, understanding and motivation throughout my life.

Nattapon Aroonchote

CONTENTS

	Page
THAI ABSTRACT.....	I
ENGLISH ABSTRACT.....	II
ACKNOWLEDGEMENT.....	III
CONTENTS.....	IV
LIST OF TABLES.....	VII
LIST OF FIGURES	VIII
CHAPTER 1 INTRODUCTION.....	1
1.1 Statement and Significance of the Problem.....	1
1.2 Goal and Objectives.....	2
1.3 Scopes.....	2
1.4 Expected Benefits.....	3
CHAPTER 2 PLASAMA SPRAY COATING PROCESS.....	4
2.1 Plasma Spray Coating	4
2.2 Plasma Spray coating Robot	6
2.3 Plasma Spray Station	8
2.4 Work Piece and Fixers	10
2.5 Spraying Condition	11
2.5.1 Coating Parameters	11
2.5.2 Spraying Pattern	12
2.6 Tool Path Planning	14
2.6.1 Software Tool.....	14
2.6.2 Coating Area Selection.....	16
2.6.3 Automated Tool Path Generation	18

CONTENTS (CONT.)

Page

2.7 Robot Simulation:20

2.8 Plasma Spray Coating Operation.....:21

CHAPTER 3 COLLISION AVOIDANCE AND TOOL PATH ADAPTATION:22

3.1 Tool Path Data:22

3.2 Collision Detection:23

3.3 Tool Path Adaptation Algorithm.....:28

 3.3.1 Physical Constrain Considering:28

 3.3.2 Define Adjustment direction:30

 3.3.3 Tool Path Adaptation procedure.....:31

CHAPTER 4 TOOL PATH IMPROVING FOR SMOOTHLY MOTION.....:34

4.1 Robot Operation Testing.....:34

 4.1.1 Robot Command:34

4.2 Define Actual Tool Center Point Speed (TCP Speed).....:35

 4.2.1 Tool Center Point Speed Signal:35

 4.2.2 ABB Test Signal Viewer:36

 4.2.3 Actual TCP Speed Graph:38

 4.2.4 TCP Speed Problem Investigation:39

4.3 Work Piece Curvature Consideration and Tool Path Regenerating.....:42

 4.3.1 Creating a lot of Spots Along the Length of the Transition Piece.....:43

 4.3.2 Considering All Point Data And Choose the Stops.....:43

 4.3.3 Creating a New Tool Path.....:47

4.4 Robot Command Modification:48

 4.4.1 Robot Move Instruction Usage:48

 4.4.2 Zone for Robot Movement.....:49

CONTENTS (CONT.)

	Page
4.4.3 Path Zone Modification	51
4.4.4 Examining the result of the zone adjusting	51
CHAPTER 5 RESULTS AND DICUSSIONS.....	54
5.1 Effects of Collision Avoidance and Tool Path Adaptation	54
5.2 Effects of Robot Motion Improving	56
5.2.1 The Effects from Path Zone Modification	56
5.2.2 The Effects from Tool Path Regenerating By Curvature Consideration.....	58
5.3 Manual Tool Path Modification for some difficult and point	60
5.3 The Comparison between the Developed Software and Commercial Software	62
CHAPTER 6 CONCLUSION AND SUGGESTIONS.....	64
6.1 Conclusion.....	64
6.2 Suggestions.....	64
REFERENCES.....	66
BIOGRAPHY.....	67

LIST OF TABLES

	Page
4.1 Sampling point selection on lower by changing degrees of the normal vector.....	45
4.2 Sampling point selection on upper by changing degrees of the normal vector.....	46
5.1 The tool path adaptation result of transition piece model 701F	56
5.2 The tool path adaptation result of transition piece model 9F	57



LIST OF FIGURES

	Page
2.1 (a) An example of turbine system of gas turbine power plants	
(b) The components of Combustor Basket and Transition Piece inside gas turbine power plants	5
2.2 The form of plasma spray gun which changes the spray material to be plasma in order to spray on the surface of the piece	6
2.3 Redundant-robot-based Painting System for Variable Cross-section S-shape Pipe	7
2.4 Steward-platform-based inlet duct painting system	7
2.5 ABB Robot IRB 6650.....	8
2.6 Turn Table and Spraying Tool	9
2.7 Robot Plasma Spray station	9
2.8 Several models of transition pieces	10
2.9 The attaching of the piece on a turn table	11
2.10 Dividing the coating part into two parts at the bending part of the piece	12
2.11 An illustration of the over coating area	13
2.12 An illustration of tool path that moves in and out along the length of the piece	14
2.13 Software tool overview	15
2.14 Internal Surface of M701F	16
2.15 Internal Surface and 3D Comparison	17
2.16 The tool path area determined by the user	17
2.17 Spots on the upper and lower parts of cross section plane when the cross section plane is 22...18	18
2.18 Projection of Cross Section Plane	19
2.19 Forming 22 sections when each section has 400 projection points	19
2.20 The illustration of path data from the software	20
2.21 Simulation software	21
2.22 Dry Run on Robot Station	21
3.1 General Framework for Collision Checking Function	23
3.2 The collision pattern that occurs when the robot is spraying the lower part of transition piece and the display of collision detecting	25

LIST OF FIGURES (CONT.) FIGURES

	Page
3.3 The collision pattern that occurs when the robot is spraying the side of transition piece and the display of collision detecting	26
3.4 The collision pattern that occurs when the robot is spraying the upper part of transition piece and the display of collision detecting	27
3.5 The robot position when there is no collision and the display of collision detecting showing “Not found collision”	28
3.6 The adjusting to avoid the collision by turning the spraying gun around the deposition point into the center of the transition piece	29
3.7 Rotating Axis	30
3.8 Coating Orientation Modification	31
3.9 The automatic adjustment in the developed software	32
3.10 The table showing the result of spraying direction adjusting	33
4.1 Tool Center Point	36
4.2 ABB test signal viewer	37
4.3 Tool path data 8800 point	38
4.4 TCP speed Graph	38
4.5 Tool path data showing the lower part spraying of the transition piece	39
4.6 Actual path white alerts in the low speed area	40
4.7 Actual path whit alerts in the low speed area (the bending part).....	40
4.8 The changing pattern of the orientation	41
4.9 Sampling point on the surface both the upper and lower parts of the piece1.....	43
4.10 Normal vector of each sampling point	44
4.11 Tool path (old version).....	47
4.12 New tool path (considering from the bending).....	47
4.13 The zone for the TCP path	50

LIST OF FIGURES (CONT.) FIGURES

	Page
4.14 The zone for reorientation of the tool	
a) three programmed positions, the last with different tool orientation.	
b) program execution if all positions are stop points.	
c) program execution if the middle position is a fly-by point.....	51
4.15 The new tool path	52
4.16 Spraying distance error	53
5.1 Root moving on Collision Free Tool Path in Robot Simulation	54
5.2 The robot working on Transition Piece Model 9FA	55
5.3 TCP speed Graph when Zone is changed to 200.....	57
5.4 Single round TCP speed Graph when Zone is changed to 200.....	57
5.5 The new tool path from the Curvature Consideration.....	58
5.6 TCP speed Graph of the new tool path from the Curvature Consideration and Zone Modification.....	59
5.7 Single round TCP speed Graph of the new tool path from Curvature Consideration and Zone Modification.....	60
5.8 Interface to adjust the spray gun for each point individually.....	61
5.9 The spraying gun adjustment at a position on the table showing spraying path of the user.....	61

CHAPTER 1

INTRODUCTION

1.1 Statement and Significance of the Problems

Plasma Spray is the spraying of molten or heat softened material for applying Thermal Barrier Coating (TBC) onto a surface to provide a protective coating. The plasma spray coating process is widely applied by multi-axis industrial robot. Generally, robot trajectories are generated by manual jock and teaching at each via point. This practice is convenient for coating a simple model but on the other hand, it is a very difficult task for coating a complex model. Obtaining complex robot motion by manual jock is time-consuming, expensive and very difficult for robot operators. Robotic software, which is tool path planning, is very helpful to generate the robot motion path, especially robot operating with complex 3D surface. The robotic software is able to generate tool path from the 3D CAD of the piece according to the spraying area and the spraying distance data which is set by the user. The tool paths are in Cartesian space which usually comprises of position and orientation for each point on the path in order to determine the corresponding joint position.

The inner surface plasma spray coating of transition piece is considered as a case study for this research work. The transition piece, which is a part in gas turbine engine, always has a very hot air tubular flow. The inner surface plasma spray coating is necessary to prevent the damage of the transition piece. The transition piece is a multi-section shapes tubular; therefore, it is difficult to generate collision-free tool path manually. Spraying conditions for the best coating surface, location and direction of spraying are important to be considered. The location is a spraying position and the direction is spraying orientations which both are specified by transformation matrix. Plasma flame should be perpendicular to the coating surface and spraying distance should be adequate throughout the process. Therefore, tool path has been created from 3D CAD model. However, the constraints of both shape and size of the spray gun and the transition piece can cause the collision to occur in certain positions on the motion path. In robot operation, the collision is a big problem; especially, through a complex shape. The collision between any parts of the system is strictly prohibited. Since the transition piece and system equipment are expensive and the crash may cause damage:

This research focuses on tool path adaptation to flee from collision. Traditionally, the modification of robot trajectory to flee from collision is done manually. Manual modification is a very time consuming work and it is very difficult to control the coating quality which will keep spray angle and length close to the initial path as much as possible. For our work, we use software simulation to simulate plasma spray coating process for testing collision avoidance and tool path adaptation algorithm. Application and adaptation algorithm detect a collision, then it will modify tool path automatically. The automatic process on software simulation makes a lot of loss-time reduction. The automatic adaptation modifies tool path from initial path which is generated by coating condition from 3D CAD model. This can also make the application retain spraying condition to keep the coating surface good as well.

1.2 Objectives

- 1.2.1 Study the plasma spray coating process with a multi-axis robot in order to find the proper spraying pattern for spraying the internal part of the work piece which is multi-section shapes tubular.
- 1.2.2 Be able to detect a collision between the work piece and the spray gun of the tool path in simulation which will lead to the solution.
- 1.2.3 Be able to adjust the moving path in order to avoid the collision automatically under a good spraying condition and an acceptable range.
- 1.2.4 Be able to simulate a complete spraying with collision free while maintain a good spraying quality.

1.3 Scopes

- 1.3.1 Study the spraying process using plasma flame in the project “Development of Tool-Path Planning and Command-Code Generation for Robot Thermal-Spray Coating System” for spraying the internal part of the work piece which is multi-section shapes tubular in order to determine the proper spraying pattern.

- 1.3.2 Use software packages, ColDet, which is 3D collision detection library to integrated with the software tool of the project “the developing of a tool path and a set of commands for a spraying robot using plasma flame”
- 1.3.3 Design a process in adjusting the tool path with collision in order to avoid the collision automatically under a good spraying condition and an acceptable range.
- 1.3.4 Adjust plasma spray tool path to make the robot be able to move smoothly and has a proper Tool Center Point Speed (TCP Speed)

1.4 Expected Benefits

- 1.4.1 Collision Avoidance will be very beneficial in preventing a collision accident when there is a simulation prior to the real work.
- 1.4.2 To include Tool Path Adaptation function into the developed software tool will greatly save time and labor that is needed in manual adjusting of the tool path.
- 1.4.3 All of the processes found in this research will enable the most beneficial use from the exiting spraying tool and robot station.
- 1.4.4 Tool path adaptation and smoothly robot motion improving process will create a better tool path with collision free, has an appropriate torch speed and be able to control several parameters to be in the determined range.

CHAPTER 2

PLASMA SPRAY COATING PROCESS

The use of the industrial robot is very helpful since it can work in a dangerous case instead of human, such as using the robot in coating process. It also controls the coating process parameter more effectively. There are many forms of robot station depending on the task requirement and the form of the transition piece. The one that has been chosen for the study of this thesis is in form of plasma spray coating. It aims to put the coating on the internal surface of the tubular shape of the piece which is the transition piece in the gas turbine engine.

2.1 Plasma Spray coating

Nowadays, the coating with special material is generally applied in order to increase the quality of the work piece. It can endure several conditions, including both the erosion and high heat. For example, there is the use of coating of thermal barrier coatings aiming to perform the maintenance of the gas turbine engine at the power plant of Electricity Generating Authority of Thailand. The heat in the power plant is at a high level. The transition piece arranges the form of flowing patterns and transfers the burnt heat from the combustor basket to the turbine in order to make the turbine rotor rotate and make the generator produce electricity. Several parts including the transition piece and the combustor basket then need to be coated by NiCrAlY or CoNiCrAlY, TBC ZrO₂-Y₂O₃ and Chromium Carbide (Cr₂C₃ NiCr) Anti-Fret coatings at the inner part in order to prevent the damage from the heat and for extended use.

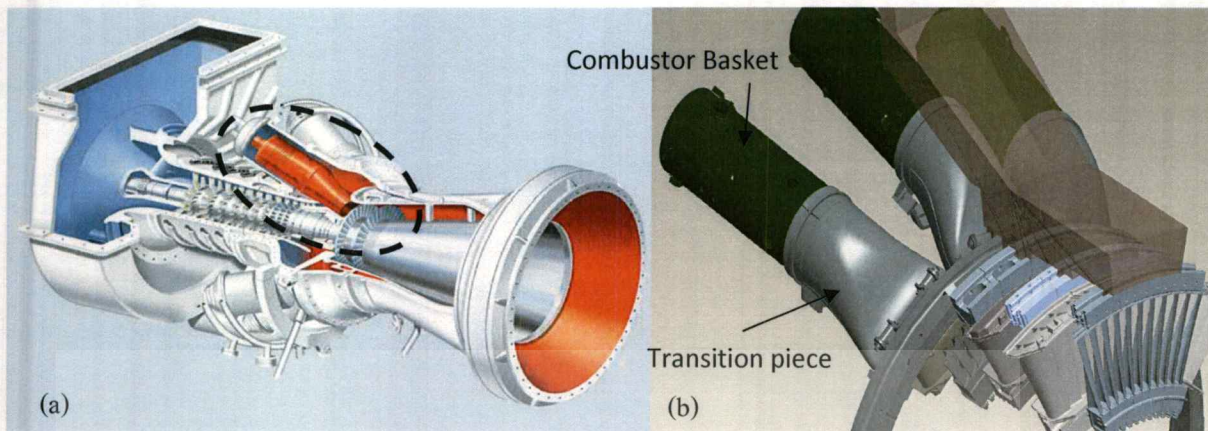


Figure 2.1 (a) An example of turbine system of gas turbine power plants

(b) The components of Combustor Basket and Transition Piece inside gas turbine power plants

The Plasma Spray Process is basically the spraying of molten or heat softened material onto a surface to provide a coating. Material in the form of powder is injected into a very high temperature plasma flame, where it is rapidly heated and accelerated to a high velocity. The hot material impacts on the substrate surface and rapidly cools forming a coating. This plasma spray process carried out correctly is called a "cold process" (relative to the substrate material being coated) as the substrate temperature can be kept low during processing avoiding damage, metallurgical changes and distortion to the substrate material.

The plasma spray gun comprises a copper anode and tungsten cathode, both of which are water cooled. Plasma gas (argon, nitrogen, hydrogen, helium) flows around the cathode and through the anode which is shaped as a constricting nozzle. The plasma is initiated by a high voltage discharge which causes localized ionization and a conductive path for a DC arc to form between cathode and anode. The resistance heating from the arc causes the gas to reach extreme temperatures, dissociate and ionize to form a plasma. The plasma exits the anode nozzle as a free or neutral plasma flame (plasma which does not carry electric current) which is quite different to the Plasma Transferred Arc coating process where the arc extends to the surface to be coated. When the plasma is stabilized ready for spraying the electric arc extends down the nozzle, instead of shorting out to the nearest edge of the anode nozzle. This stretching of the arc is due to a thermal pinch effect. Cold gas around the surface of the water cooled anode nozzle being electrically non-conductive constricts the plasma arc, raising its temperature and velocity. Powder is fed into the plasma flame most commonly via an external

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powder port mounted near the anode nozzle exit. The powder is so rapidly heated and accelerated that spray distances can be in the order of 25 to 150 mm.

The coating process with a spray gun can be shown in Figure 2.2. The spray gun will turn the material to be in form of plasma to enable the spraying on the piece. The movement of the spray gun including the distance and the direction of the spraying are very important to the density of the coating material on the piece which really has a direct influence on the coating quality. In order to get the best coating quality, the distance between the spray gun and the coating surface must be appropriate and stable. The spray flame also should spray directly to the surface as perpendicular. The movement speed needs to be proper and smooth as well.

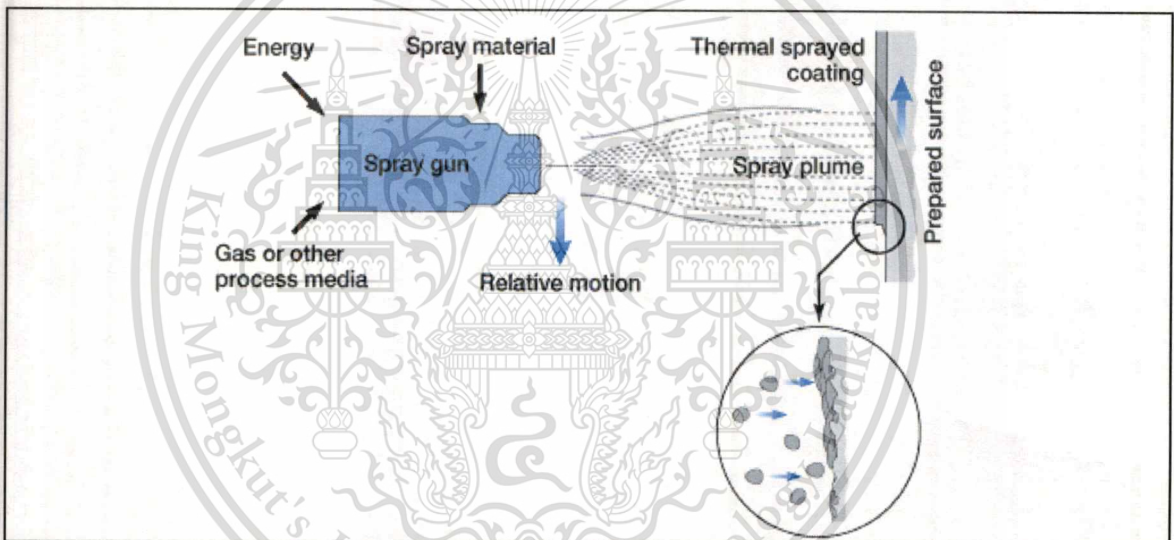


Figure 2.2 The form of plasma spray gun which changes the spray material to be plasma in order to spray on the surface of the piece

2.2 Plasma spray coating Robot

There are many types of Plasma spray robot, depending on application and task requirement. For the application which is inner surface coating for multi section shape, a specially designed robot has been created. According to the article “Redundant-robot-based Painting System for Variable Cross-section S-shape Pipe” [10], a special in-pipe robot system was researched and developed. This concept is able to spray color or coating substance on the surface of the work piece on the condition of perpendicular spraying direction and suitable spraying distance. A manipulator was added on the

spraying tool as shown in figure 2.3. However, in the practice of creating a Plasma spray coating robot, the spray torch and equipment contains so much weight. Therefore, this kind of concept is not applicable.

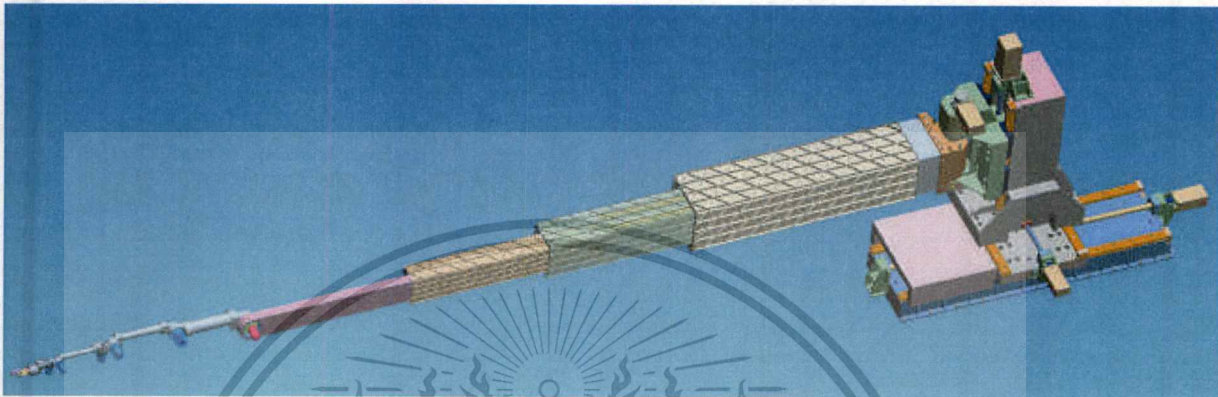


Figure 2.3 Redundant-robot-based Painting System for Variable Cross-section S-shape Pipe

There is also another kind of robot called Stewart-Platform-Based Inlet Duct the Surfaced Painting System [9] This concept allows the user to paint the inner surface of the work piece. This robot uses wheels to help with the movement into the inside of the transition piece while spraying at the same time as shown in figure 2.4. Nonetheless, Plasma spray coating process produces high heat which can causes excess heat to the coating surface. This factor makes moving the wheels into the piece not proper. Moreover, if the work piece is touched, the quality of the work can be decreased.

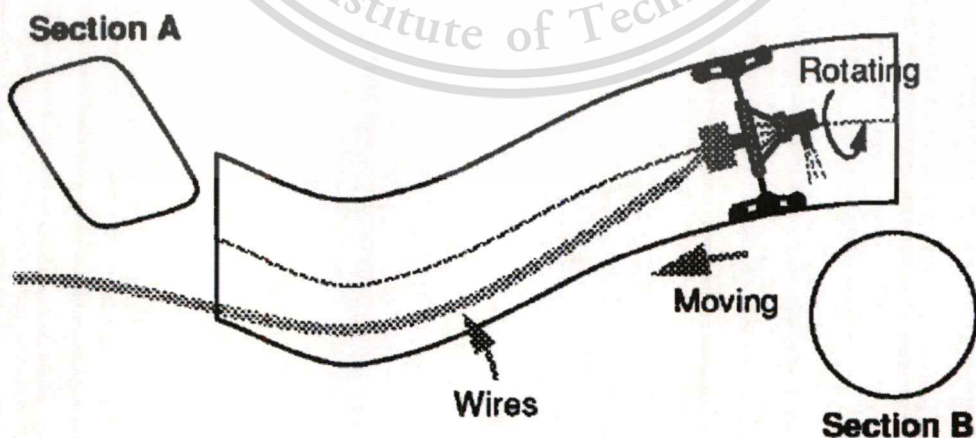


Figure 2.4 Stewart-platform-based inlet duct painting system

These two cases discussed above prove that the use of ABB robot with long type spraying gun can save budget and can be more convenient for the working process. This application allows the development of the old station to be more effective in the usage.

2.3 Plasma Spray station

The components of the coating robot system of egad plasma spray station consist of an industrial robot ABB IRB 6650 which has six-axis movement as shown in Figure 2.5. Also, there is a robot control cabinet IRC 5, Process Module on Single Cabinet, which contains Interface Board for connecting with the control part. The coating process is installed within the cabinet in the part called Process Module. The robot is installed in the coating room together with the tools supporting Air Plasma Spray (APS). In the coating process, the work piece will be attached to a fixture which is specifically designed for the shape of each piece. The worker needs to follow the instruction in order to attach the piece to the fixture which is set on a turn table. The piece will be able to move in two ways; tilting in or out from the robot and rotating around the upper axis of the turn table. The turn table makes it easier to adjust the position of the piece for the coating process and also enables the robot to insert the long APS spray gun into the piece as shown in Figure 2.6.

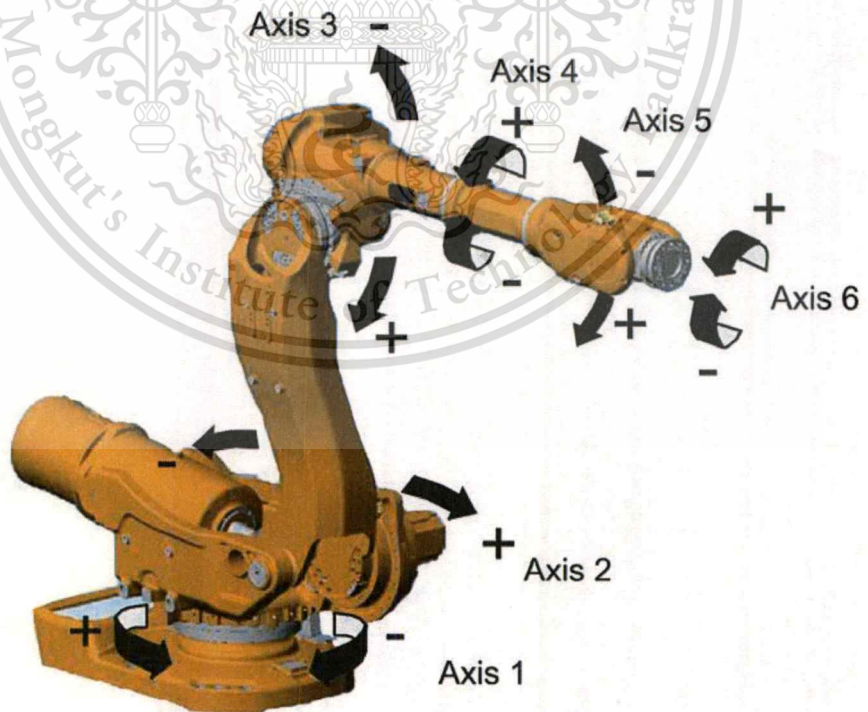


Figure 2.5 ABB Robot IRB 6650

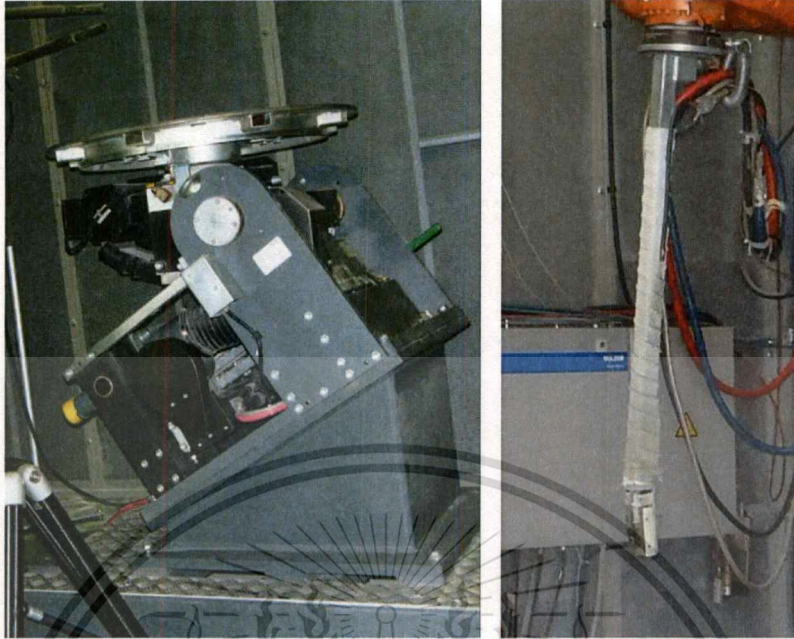


Figure 2.6 Turn Table and Spraying Tool



Figure 2.7 Robot Plasma Spray station

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2.4 Work Piece and Fixers

At Electricity Generating Authority of Thailand, there are many models of gas turbine engine, so there are various parts that need to be coated, such as transition piece and combustor basket. This thesis focuses on Thermal Barrier Coating for internal surface of transition piece which consists of many models as shown in Figure 2.8. The user needs fixers particularly for each model.



Figure 2.8 Several models of transition pieces

Transition Piece Model M701F is an example of plasma spray coating process. In this thesis, it is placed on a turntable by the fixers as show in Figure 2.9. It shows that the fixer attaches the piece on the turn table to be in the exact spot every time. Therefore, the user always needs to follow the process and adjust the tool according to the referring point.

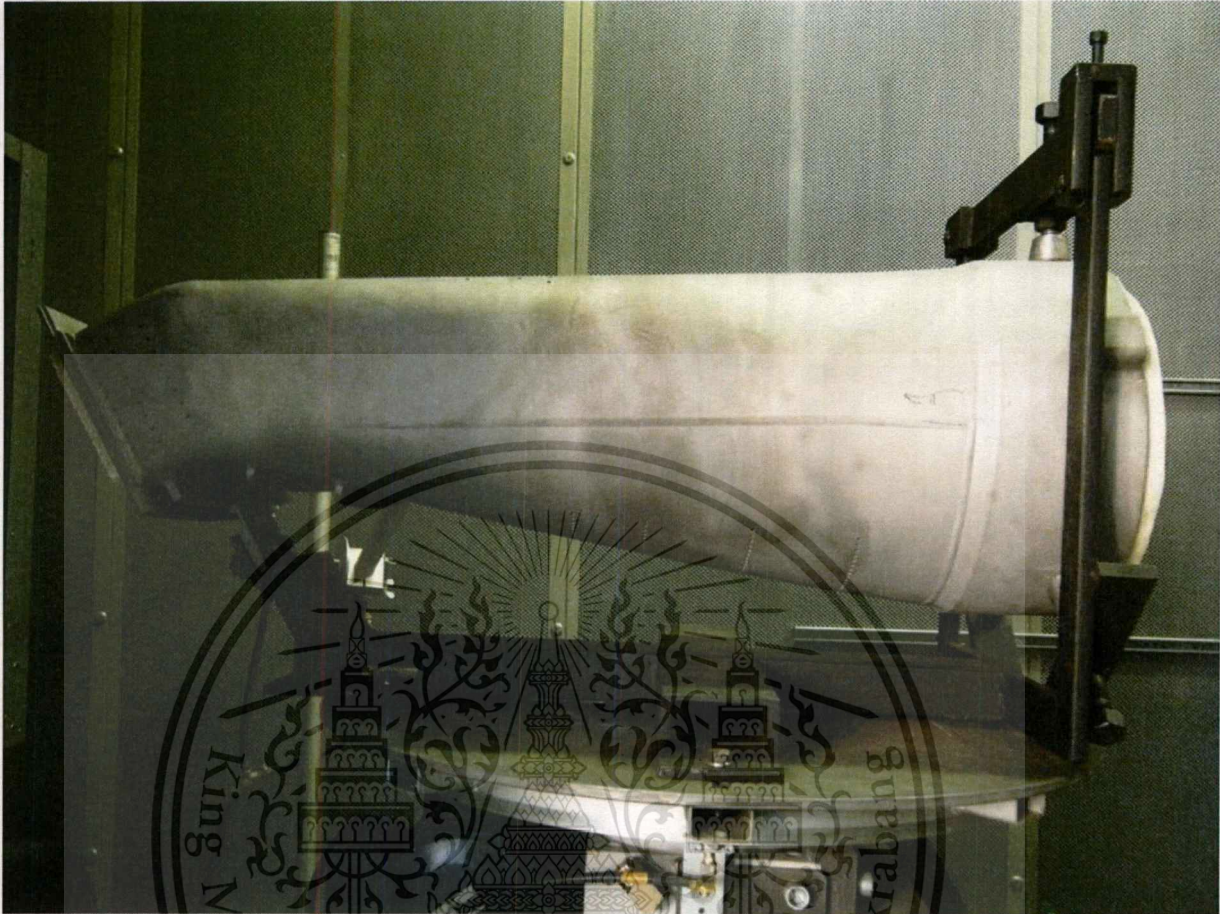


Figure 2.9 The attaching of the piece on a turn table

2.5 Spraying Condition

There are many parameters and conditions which can affect the coating quality; therefore, the experiment is needed in order to find the most suitable coating parameters and spraying pattern. The coating parameters relate to this thesis are spraying distance, spraying angle and torch speed.

2.5.1 Coating Parameters

According to the article *Supervisory Level Control of Robot Plasma Spray Coating Process with Task Level Modification Based on Process Database and Evaluation of off-angle thermal spray*, the researcher has conducted an experiment and analyzed to find the most suitable coating parameters, together with the acceptable range. Therefore, we are able to apply the result of the experiment and analysis for the best coating guilty. The spraying distance (the distance between the

spray gun and the coating surface) should be 60 mm. while the spraying angle should be 90 degree (perpendicular to the surface) and the torch speed should be stable at 600 mm/s.

However, in the reality, it is almost impossible to determine several parameters according to spraying conditions. Therefore, we need to conclude and analyze the result of the experiment to find the range of variables. The acceptable range of the variables should be as follow:

Spraying distance should be between 55mm. – 65mm.

Spraying angle should not be away from the perpendicular more than 30 degrees.

Torch speed must not be less than 400mm/s

However, even if the variables have the acceptable range, we need to keep it close to the best value in order to keep the coating surface good as well.

2.5.2 Spraying Pattern

Transition piece plasma spray coating with separate spray paths is a way to operate without collision s same as *Optimisation of the robot controlled plasma spraying of thermal barrier coating for gas turbine transition duct*. We have applied this idea in the experiment concerning the coating of transition piece Model M701F. We have divided the coating part into two parts at the bending part of the piece and order the robot to insert and spray each side.

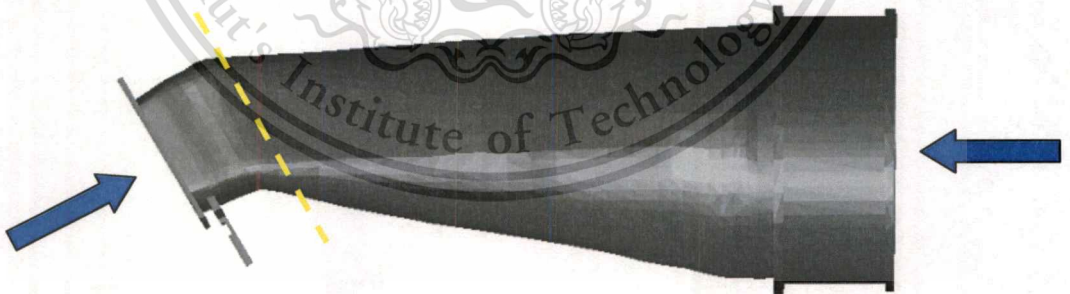


Figure 2.10 Dividing the coating part into two parts at the bending part of the piece

There is an advantage in designing the tool path for this kind of coating because there are less collision spots comparing to the piece that was sprayed from one direction by the robot. However, when we divide the tool path into many parts and spray each part at a time, it is difficult to control

coating thickness on the coating joints. Bad coating joints might be a cause of problem. The problem can occur due to the gap between the joints or over-coating at the joints. The gap can cause the effectiveness of heating protection to decrease. In this case, during the usage where there is a lot of heat, the gap can cause the piece to get damaged and has fewer lifetimes. On the other hand, the over-coating increases a risk for the piece to peel off and the peel can cause damage when it is in use.

According to the experiment of creating tool path by dividing into two parts at the bending area of the piece, we ordered the robot to spray each part while the parts were overlapped. Therefore, it turns out that coating surface result is over coating in the area as shown in Figure 2.11. The spot that was found with the most over coating is at the reverse point of the spraying tool because there is low TCP speed.



Figure 2.11 An illustration of the over coating area

For good coating surface forming, not only spraying distance and spraying angle are to be considered but also spraying should be done continually so that the piece will not face any of the troubles stated above. In order to get a continual spraying, we create the tool path which moves back

and forth along the length of the transition piece. Also, the returning point should be away from the tip of the tubular piece in order to prevent it from over-coating at the tip as well. The form of movement has been shown in Figure 2.12

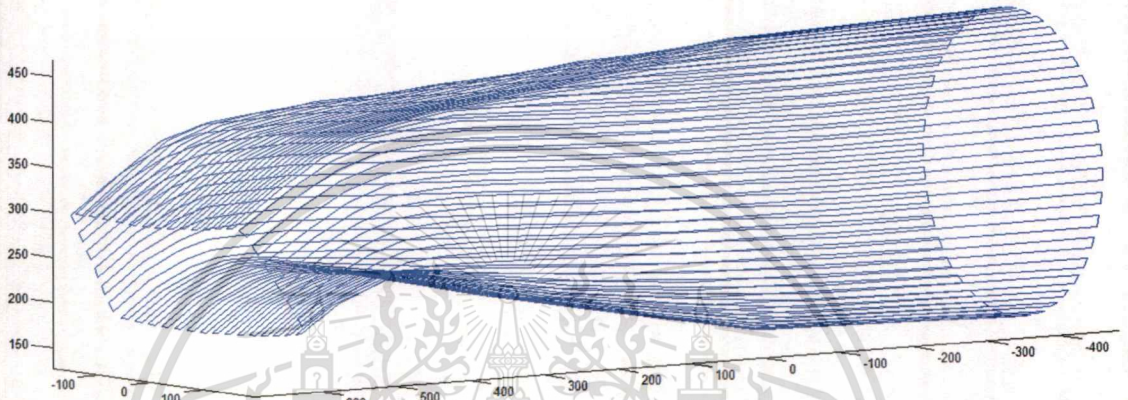


Figure 2.12 An illustration of tool path that moves in and out along the length of the piece

2.6 Tool Path Planning

2.6.1 Software Tool

The tool path was created by a software tool which was developed in a research project concerning the developing of the tool path creating system and commands for the plasma spraying robot. This software will enable more effective use of robots and other tools existed in plasma spray station because this software can create a set of commands to control the robot and the two-axis turntable quickly. There are three main processes in creating the tool path with the software tool: *Planning Level, Task Level and Process Level.*

The planning level is to prepare the components needed in creating the tool path of the robot and the turntable for spraying the piece. The first thing that we need is CAD Model of each part of the robot, such as an industrial robot ABB IRB6650, a spray gun, CAD Model of each part and the fixer for the piece. These 3D CAD Model will be in standard format .STL which will import into the

software by 3D Geometry Loader. Then, we need to select coating area from work piece in 3D Geometry and do the coating parameters selection.

The task level is the next process which will generate the tool path relying on the valued that was set by the user in the planning level. Then, we can work on the collision avoidance and tool path adaptation in robot simulation and torch speed modification to make it suitable for the movement.

The process level will transmit robot movement into the form of robot command code to send to robot controller.

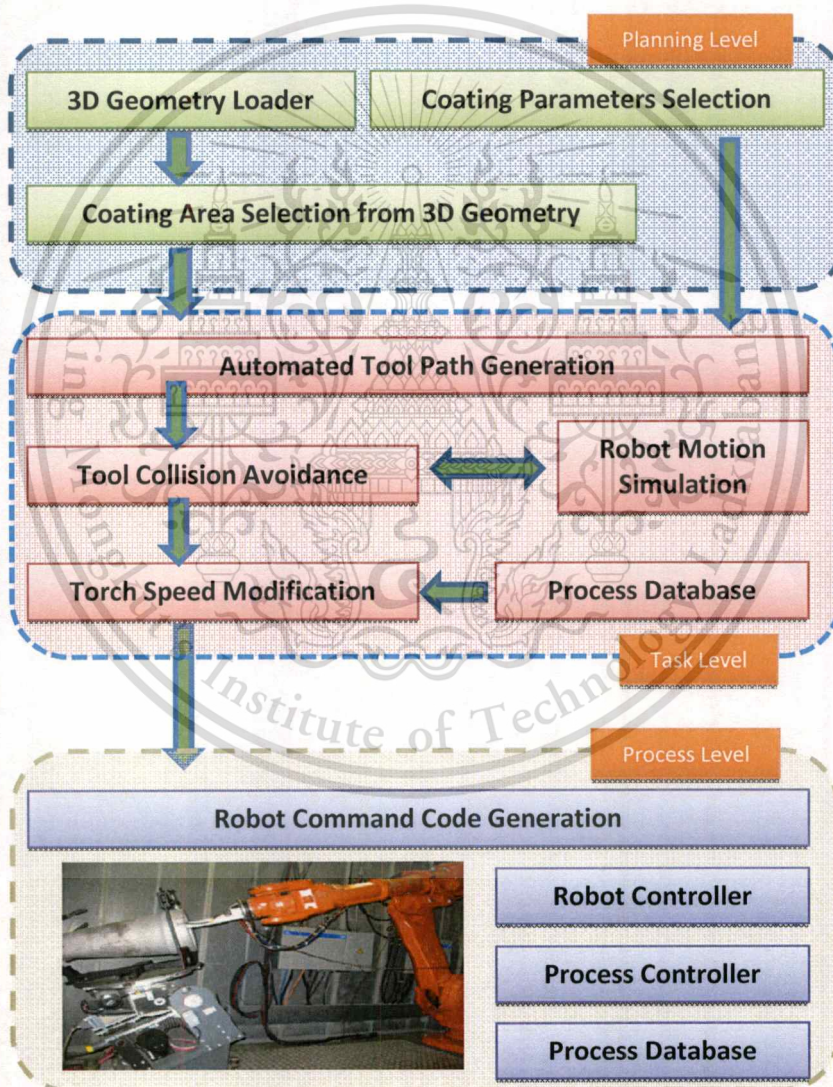


Figure 2.13 Software tool overview

2.6.2 Coating Area Selection

The user is the one who determine the coating area for the software tool which in this case is the internal surface of the transition piece Model M701F. The internal surface is obtained by the scanning the inner part of the piece to get STL surface file which is more accurate than scanning the outside of the piece. Then, we operate the offset to create the internal surface of the piece. Figure 2.14 shows Internal Surface of M701F obtaining from scanning and offsetting by creating a complete surface. Whereas Figure 2.15 shows the comparison between the Internal Surface and 3D CAD model, it is clear that the tip of each transition piece is left out to make the room for the reverse point for the tool path in order to reverse away from the tip of the tubular piece.



Figure 2.14 Internal Surface of M701F

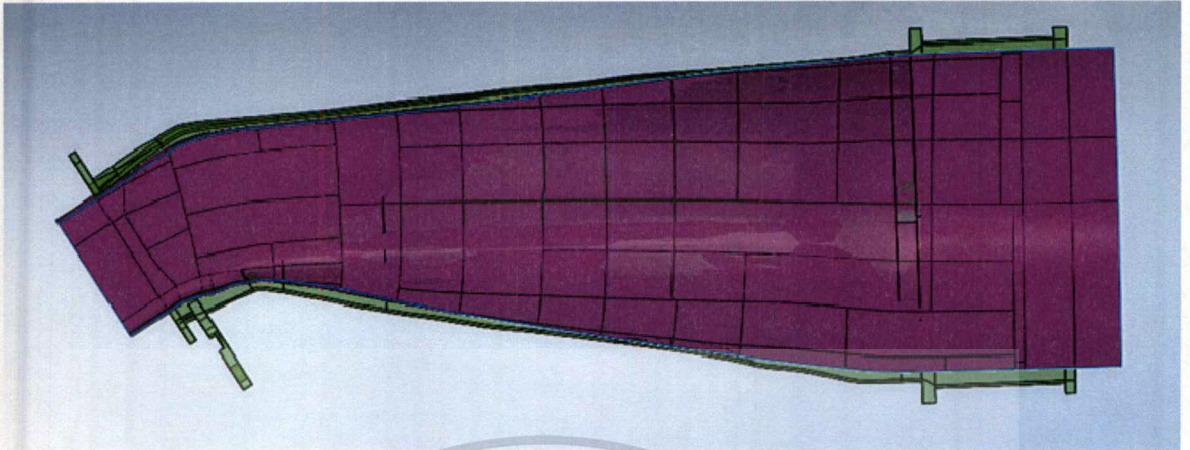


Figure 2.15 Internal Surface and 3D Comparison

The user needs to determine four spots on the internal surface in order to limit the creating the tool path as show in Figure 2.16. The software tool will create a tool path that will move in and out ordering the robot to insert the spraying tool to start the work from the round side of the piece.

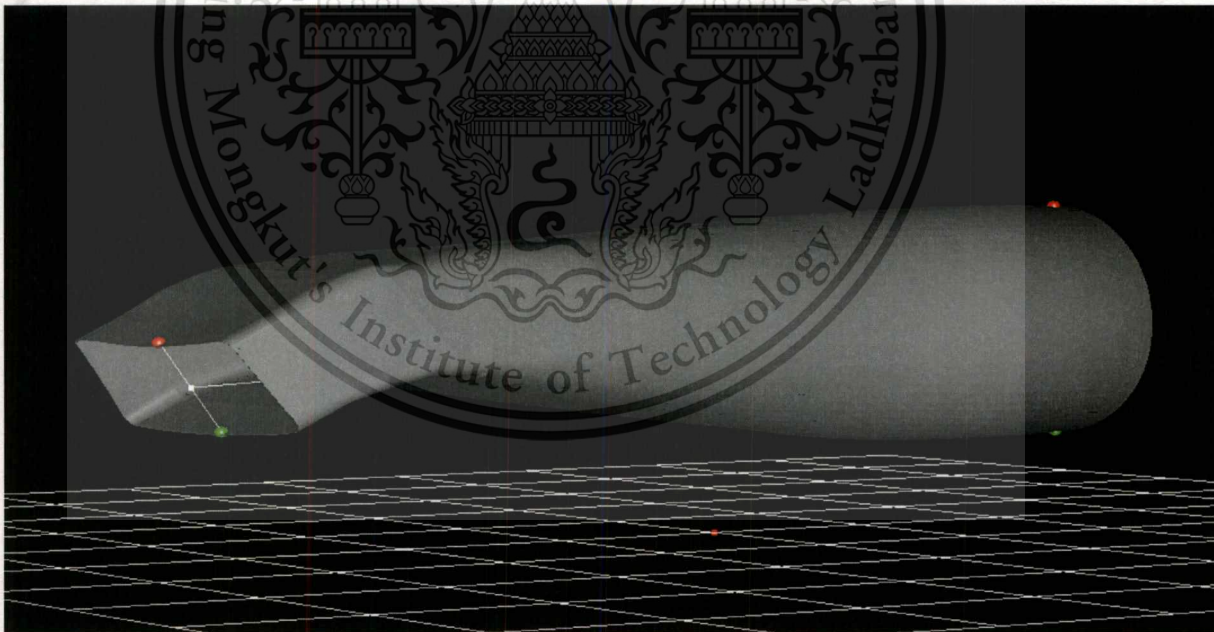


Figure 2.16 The tool path area determined by the user

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2.6.3 Automated Tool Path Generation

In creating the tool path for the internal part of the piece, we apply the method called projection from the cross section center point to the inner area of the piece. Therefore, the parameter that must be set for the software is the number of cross section plane. In this case, when the numbers of sections is set to be 22, the software will create the path in pair to form a plane along the length of tubular piece both on the upper and the lower part. The cross section plane markers are the spots that locate the positions of cross section plane. The cross section plane will be on the link between the upper and lower cross section markers. Figure 2.17 shows the position of cross section plane markers and cross section planes created by the software by default. The software will also determine the distance to be equal along the upper line in section. The distance between each section is equal to the total length of the whole pipe divided by the number of section set by the user.

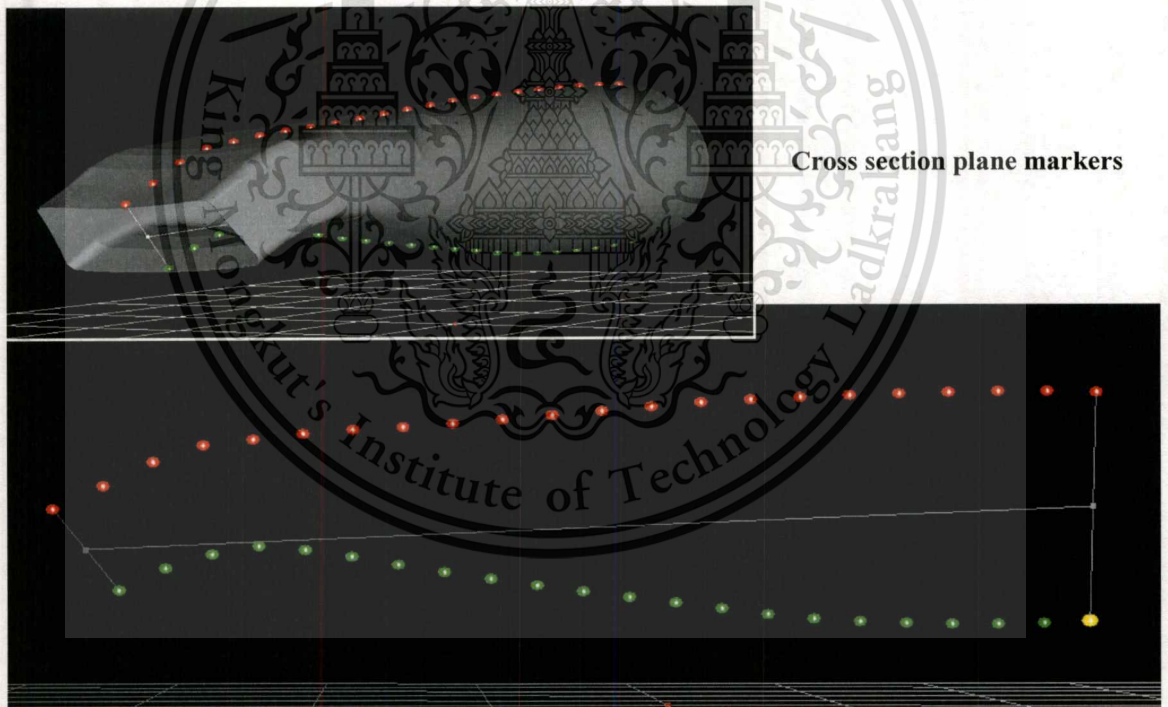


Figure 2.17 Spots on the upper and lower parts of cross section plane when the cross section plane is 22

CHAPTER 3

COLLISION AVOIDANCE AND TOOL PATH ADAPTATION

There are many methods that we can use in order to solve the problem of spraying the inside of the transition piece; both the designing and the building of a specific spraying robot. However, to save the energy, we choose to make the best use of the spraying tool and robot station that already exist. We choose to adapt the tool path, which was created by the software mentioned in chapter 2, to make it be able to avoid the collision. To do this, we add the collision avoidance and tool path adaptation into the developed software tool which should greatly help saving time and labor used in manual fixation of the tool path.

3.1 Tool Path Data

The tool path data, which is built automatically by the software, creates a lot of spots on the internal surface of the work piece's tool path data while the tool path parameter is set by the user. These spots will be arranged in order so that the robot will move following the spots. Each spot consists of position and orientation which both are specified by transformation matrix. The position is the location the spraying gun will spray the plasma flame and the coating material on the piece. The orientation indicates the direction of the spraying gun including the moving pattern of the gun. In figure 3 below, we can see the form of transformation matrix of every path data or so called target.

$$T_{Path} = \begin{bmatrix} R_{Path} & P_{Path} \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} R_{xx} & R_{yx} & R_{zx} & P_x \\ R_{xy} & R_{yy} & R_{zy} & P_y \\ R_{xz} & R_{yz} & R_{zz} & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The software will calculate to find inverse kinematics and choose the appropriate robot configuration. For each tool path, the data, which was arranged on the tool path automatically, has an

orientation. This orientation can set the plasma flame to be perpendicular to the coating surface which does not work in some positions. Therefore, we need to stimulate to detect the collision and make an adaptation at the collision position in the simulation.

3.2 Collision Detection

In this section, I describe a collision detection function for the internal plasma spray coating process and the function for collision detection in the software tool. The researcher used existing software packages for collision detection called ColDet. ColDet is a 3D collision detection library for generic polyhedral. Its purpose is mainly for 3D games where accurate detection is needed between two non-simple objects. It is written in standard C++ and can be compiled on Visual C++. Tool path generation software and robot simulation are created in the basis of standard C++ as well, thus it is convenient for the researcher to add collision detection function into the software.

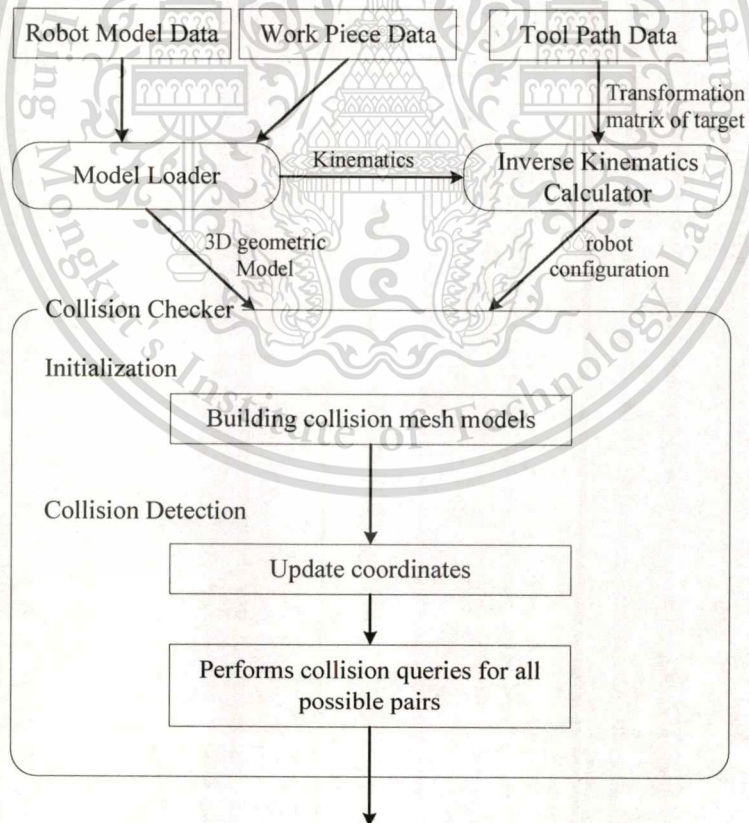


Figure 3.1 General Framework for Collision Checking Function

Fig.3.1 shows the general framework of collision detection system for a robot. Following two information are required for finding collided object pair. The first is 3D geometric model information for objects. Usually it requires polygon triangles of the object surfaces. Another is transformation matrix of each object for updating current coordinates (the position and rotation) of the object. Then we are able to perform collision query to see if there collided objects using the 3D geometric model information and the transformation matrix information.

A robot manufacturer usually provides the robot model data which contains the 3D geometric model of each link and the joint or kinematics information that which link pair is connected each other. Therefore the software for loading this model data is to be developed, which is illustrated as a "Model Loader" in the figure. The other required software is "Inverse Kinematics Calculator" which calculates a robot configuration from the tool path data by using kinematics information of a robot. For each target, there could be many configurations. It chooses the robot configuration by keeping all robots' joints angle move at the minimum from the previous one.

The program will stimulate to perform the actions according to the calculation of the Inverse Kinematics Calculator and then choose the joint angle of each link. In the meanwhile, collision checker is performing the detecting at all time. Whenever there is a collision between the piece and the spraying gun, the checker will inform the collision position through an output report display. The display will show much information such as collision position, robot position, tool position and turntable position. The spraying process will spray the whole piece continually. However, there are three types of collisions that can happen between the processes: the lower part, the side and the upper part of the transition piece. Most of the time, the pattern of the collision are quite the same which is when the spraying gun is perpendicular to the coating surface, the longer part of the spraying gun will hit the upper part of the piece. Figure 3.2-3.4 show the form of the collision when the spraying gun is perpendicular to the coating surface in several areas. The figure also shows the result of the collision detecting performed by collision checker. However, if the collision does not happen, the display will show 'Not Found Collision' in the output report as in Figure 3.5

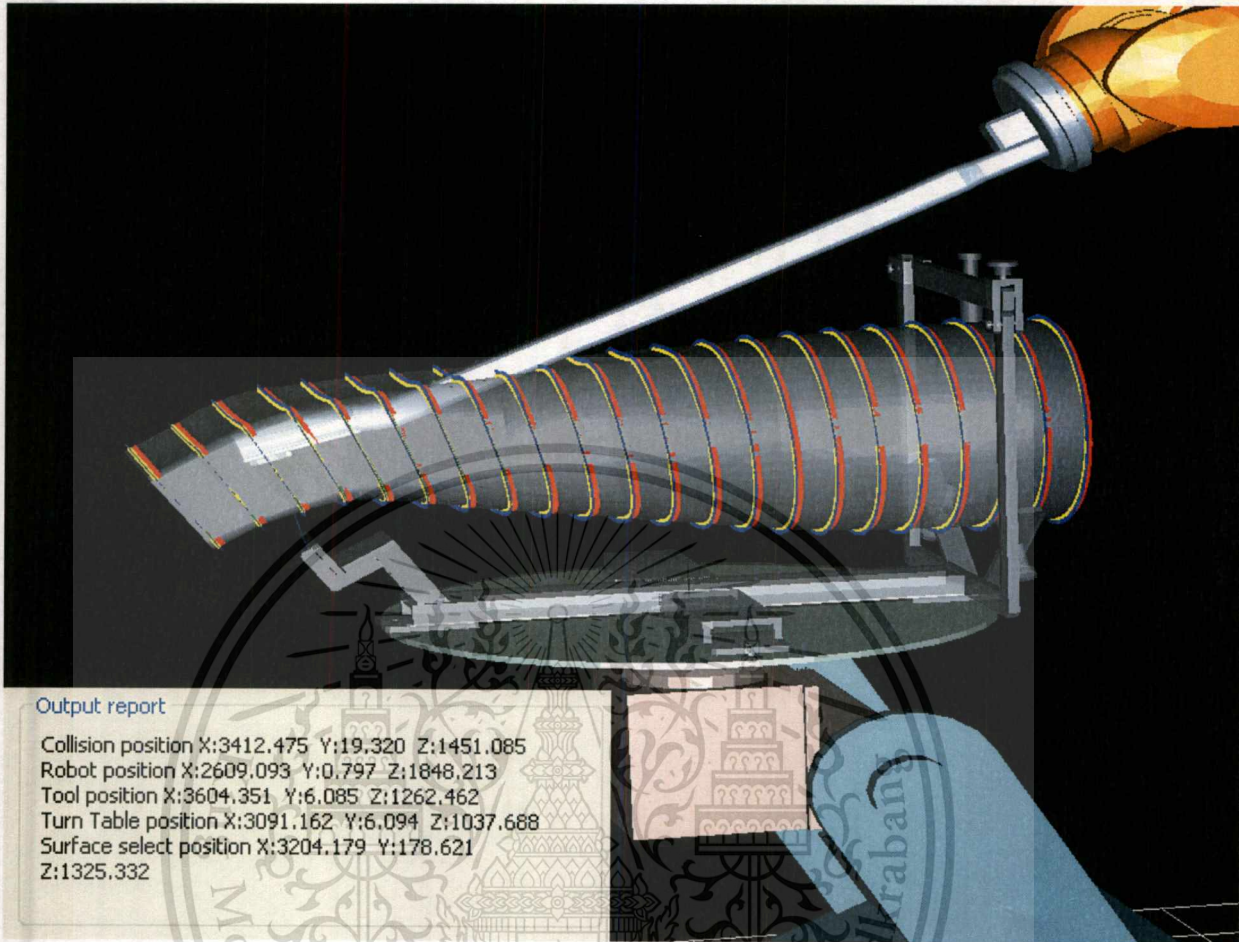


Figure 3.2 The collision pattern that occurs when the robot is spraying the lower part of transition piece and the display of collision detecting

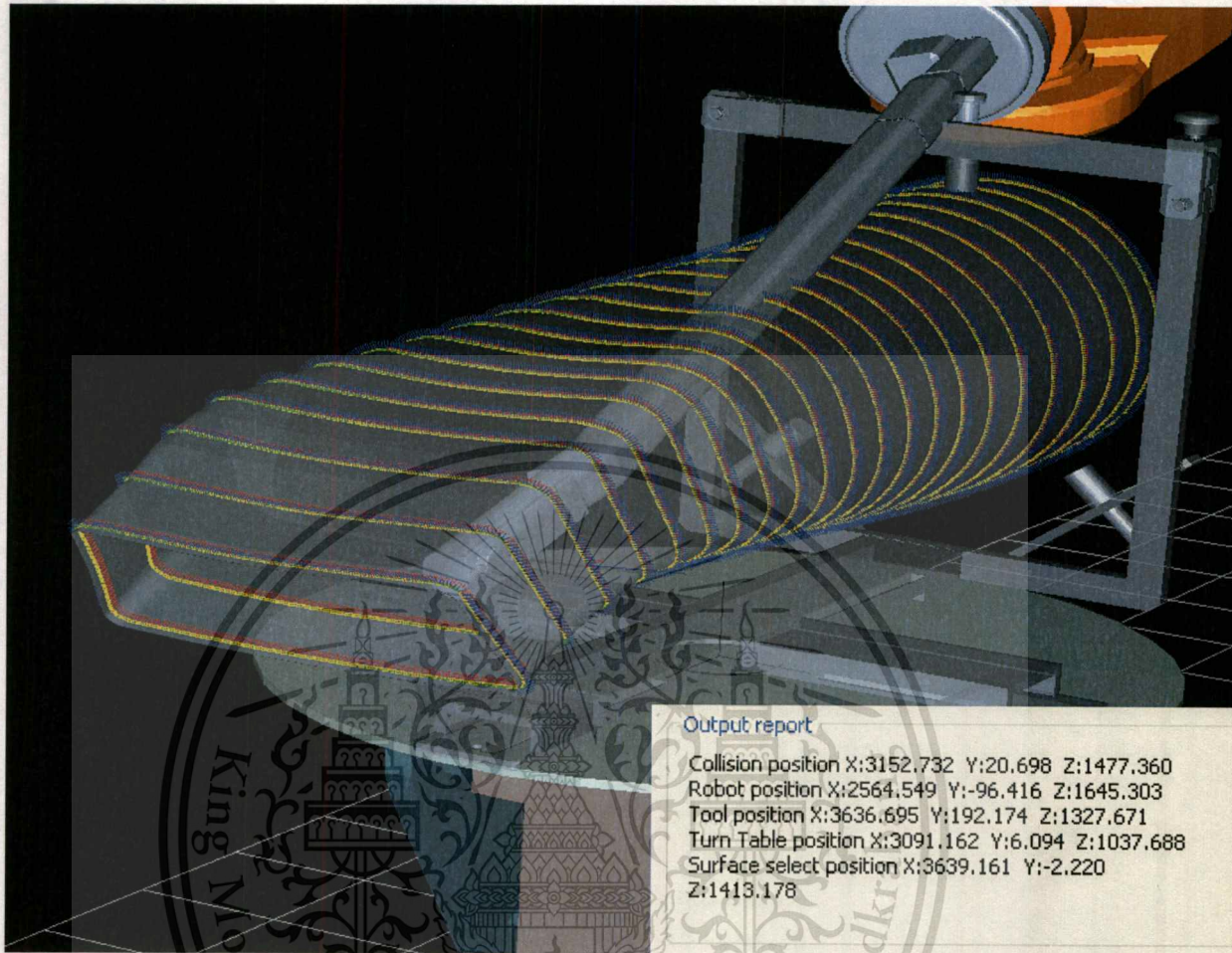


Figure 3.3 The collision pattern that occurs when the robot is spraying the side of transition piece and the display of collision detecting

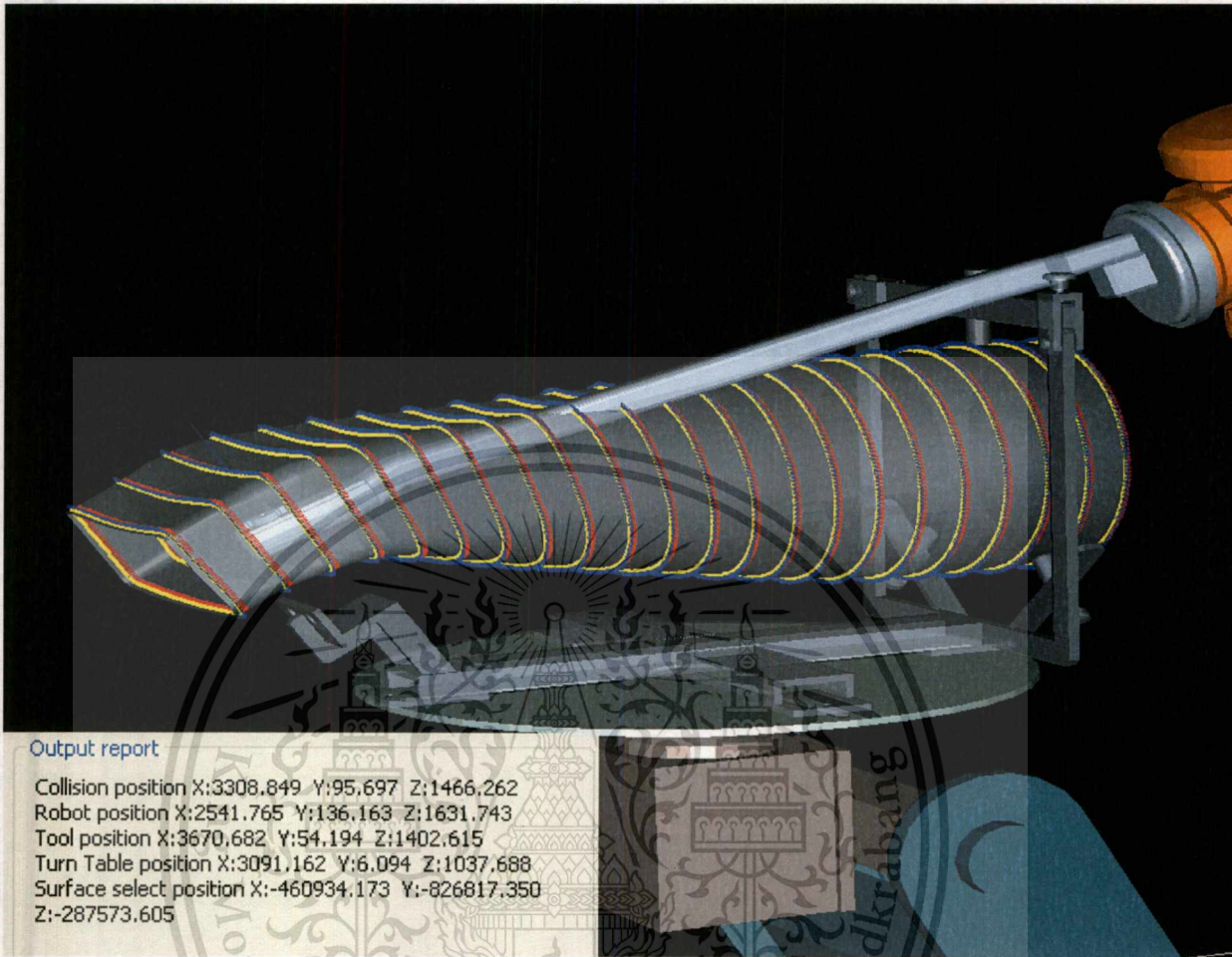


Figure 3.4 The collision pattern that occurs when the robot is spraying the upper part of transition piece and the display of collision detecting

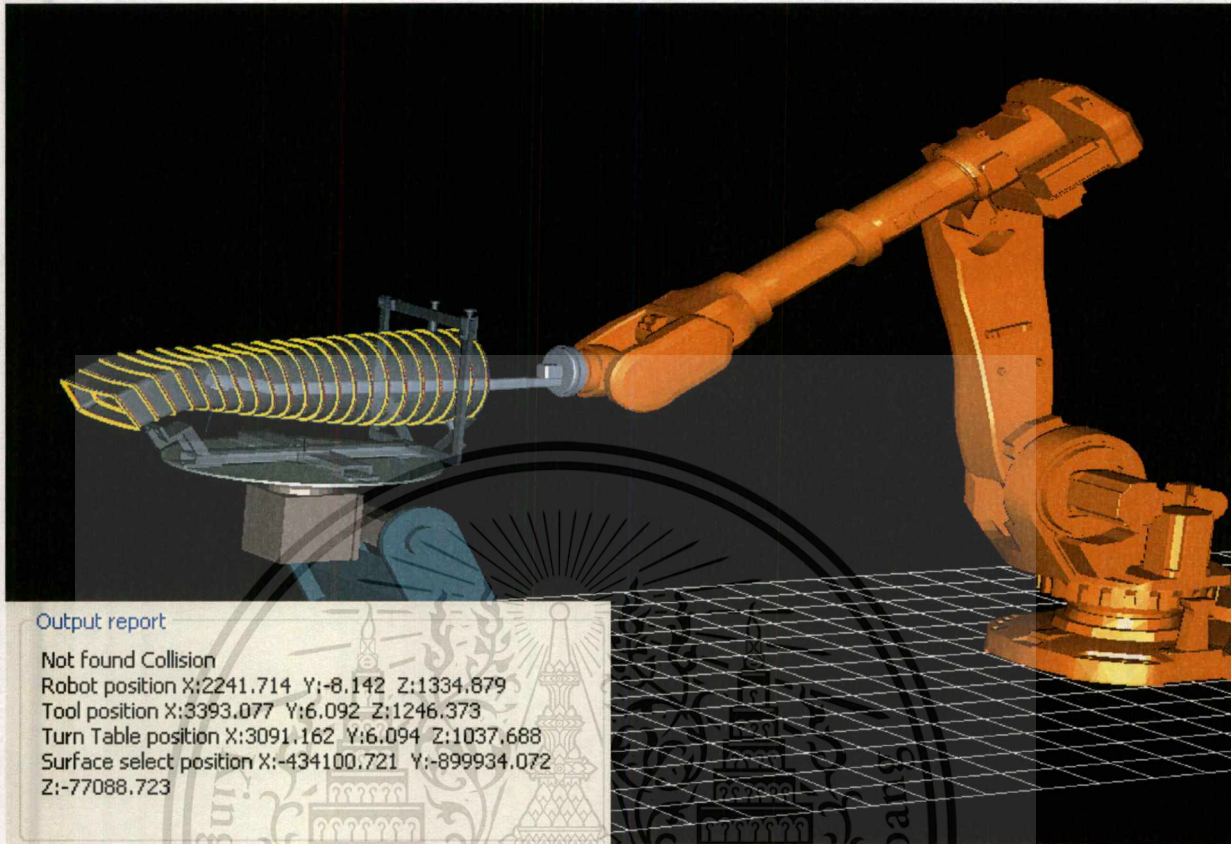


Figure 3.5 The robot position when there is no collision and the display of collision detecting showing “Not found collision”

3.3 Tool Path Adaptation Algorithm

3.3.1 Physical Constrain Considering

According to physical constraint of Transition Piece and spraying tool, the inner space of transition piece is freely available place for gun adaptation. However, the spraying direction and distance have to be considered seriously in order to get the coating surface as the specification. Consequently, the adjustment principles of the spraying gun alignment to the center axis of the transition piece are based on no-collision and closing to the initially perfect tool path. Another important concern about the adjusting of the spraying gun is finding the turning pattern to avoid the collision around deposition point. The deposition point needs to remain the same to make sure that the plasma flame is not bent and the piece is sprayed smoothly.

In order to program the software to turn automatically to avoid the collision, we need to find the axis spot whenever the collision is detected. The axis spot should be able to make the handle of the spraying gun turn to the center part of the transition piece. The software will adjust the gun according to the axis around the deposition point which should avoid the collision.

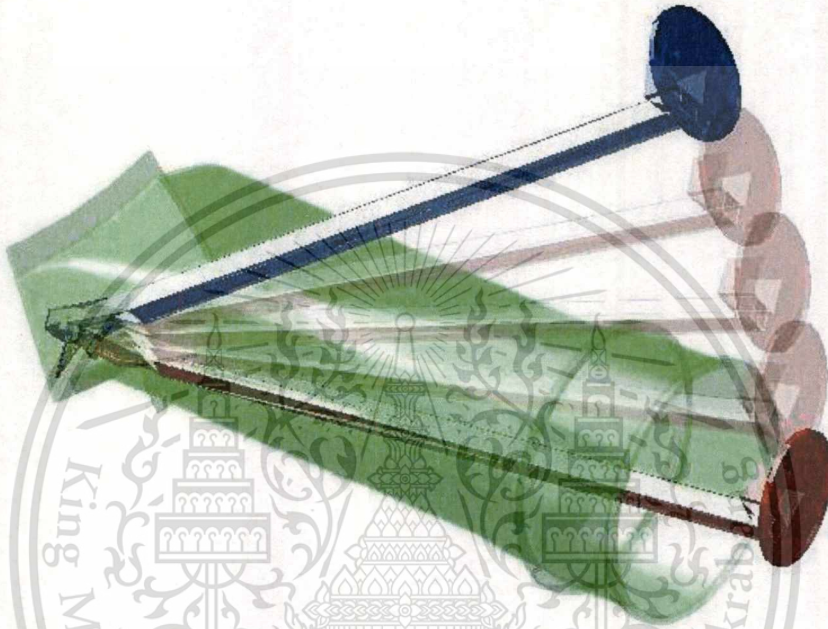


Figure 3.6 The adjusting to avoid the collision by turning the spraying gun around the deposition point into the center of the transition piece

3.3.2 Define Adjustment Direction

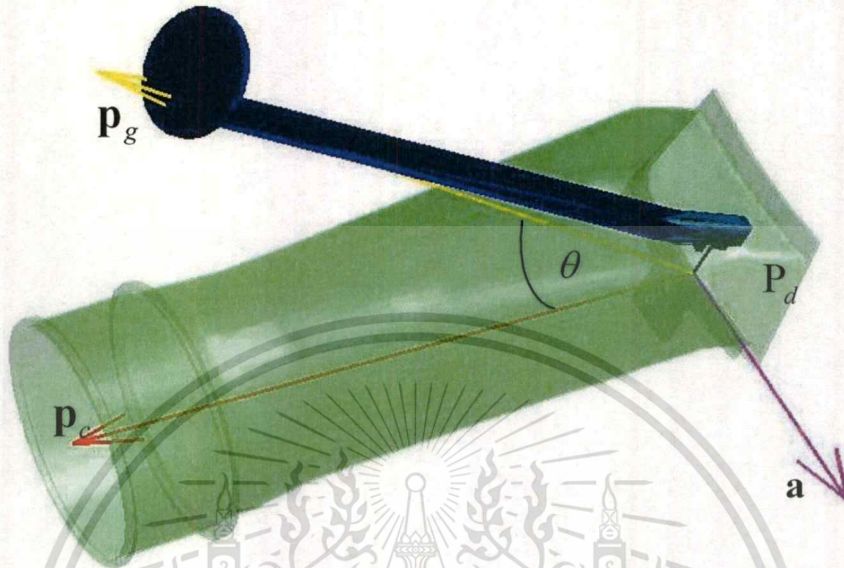


Figure 3.7 Rotating Axis

The adjustment of spraying direction is to rotate robot target coordinate frame. In order to rotate robot target coordinate frame to move to the center of the transition piece, we need to create a new specific rotating axis. At the collision point, the software defines modification direction required by creating two vectors originated at the spray deposition location P_d . The first vector \mathbf{p}_g directs through gun handle while the second vector \mathbf{p}_c directs through the middle of the circular transition piece mouth. This rotational vector could be computed as cross product of \mathbf{p}_g and \mathbf{p}_c which creates a result as vector \mathbf{a} . The vector \mathbf{a} is an arbitrary axis in rotating robot target coordinate frame which the rotational matrix for the arbitrary axis \mathbf{a} could be computed as equation (2).

$$\mathbf{R}_a(\theta) = \begin{bmatrix} a_x a_x v\theta + c\theta & a_x a_y v\theta - a_z s\theta & a_x a_z v\theta + a_y s\theta \\ a_x a_y v\theta + a_z s\theta & a_y a_y v\theta + c\theta & a_y a_z v\theta - a_x s\theta \\ a_x a_z v\theta - a_y s\theta & a_y a_z v\theta + a_x s\theta & a_z a_z v\theta + c\theta \end{bmatrix} \quad (2)$$

Where

$$c\theta = \cos \theta$$

$$s\theta = \sin \theta$$

$$v\theta = 1 - \cos \theta$$

3.3.3 Tool Path Adaptation Procedure

The adaptation of the tool path should not only avoid the collision but also retain the initial spraying angle as much as possible. As we can see from the figure 3.8, after we have modified the tool path, the spray gun will be just far enough from the collision.

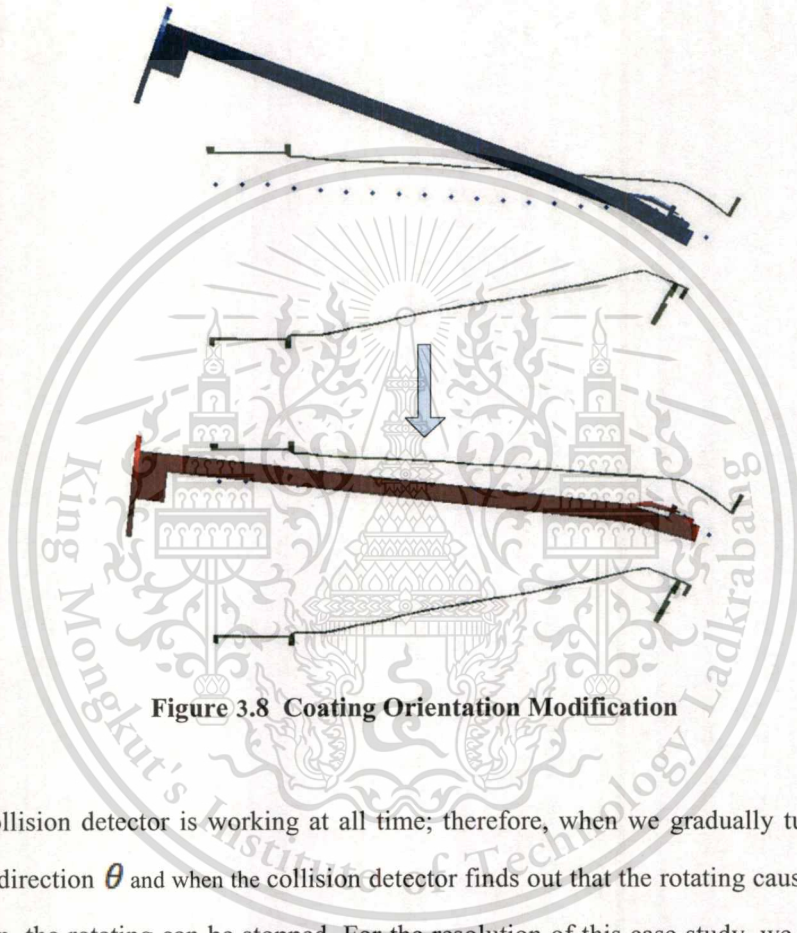


Figure 3.8 Coating Orientation Modification

The collision detector is working at all time; therefore, when we gradually turn the arbitrary axis \mathbf{a} to the direction θ and when the collision detector finds out that the rotating causes spraying free from collision, the rotating can be stopped. For the resolution of this case study, we set the arbitrary axis \mathbf{a} to rotate 1 degree at a time. For each collision, the incremental tool rotational adjustment can be computed iteratively by (3) and noted that $\Delta\theta$ is resolution step degree.

$$\mathbf{R}_{i+1} = \mathbf{R}_i \times \mathbf{R}_a(\Delta\theta) \quad (3)$$

Where \mathbf{R}_i is a current tool rotational matrix and \mathbf{R}_{i+1} is a new rotational matrix. The equation (3) is repeated until collision is not detected. The result of this algorithm can keep the spraying direction closest to the surface normal without collision.

The adaptation of tool path in form of off-line path planning in robot simulation software is shown in figure 3.9. The adaptation begins whenever there is a collision between the gun and the piece anywhere on the tool path as shown in figure 3.9-a. The robot slowly adjusts the spraying direction by rotating the spray gun to flee from collision as in figure 3.9-c. Then, the robot remembers the new adjusted direction and also calculates the changing degree. Those are used in order to consider whether it is acceptable. After that, the program will continue on its work at the next position.

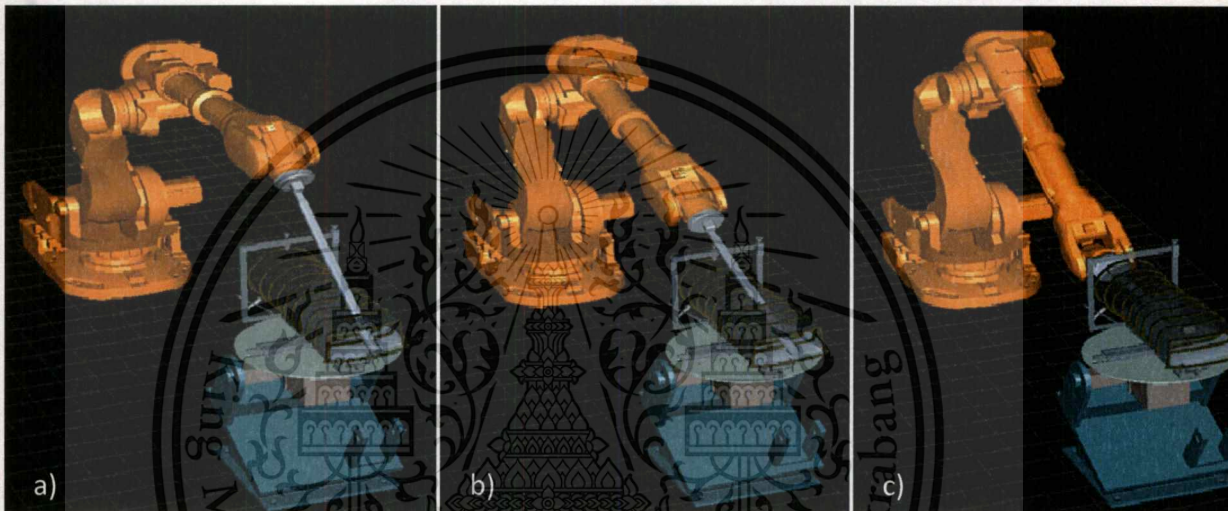


Figure 3.9 The automatic adjustment in the developed software

The result of the automatic adjustment will be recorded in the table to inform the collision position to the software user and whether the adjusting of the gun can avoid the collision in each position. Also, after the automatic adjustment, the table will inform the degree which the spraying direction is rotated as shown in figure 3.10. The collision position will be highlighted.

Path Status

Path Index	Stand of distance	Angle	Status	Remark
48	NULL	0	Pass	
49	NULL	0	Pass	
50	NULL	0	Pass	
51	NULL	0	Pass	
52	NULL	0	Pass	
53	NULL	0	Pass	
54	NULL	0	Pass	
55	NULL	0	Pass	
56	NULL	8.997432	Pass	Adjusted
57	NULL	8.990456	Pass	Adjusted
58	NULL	18.995562	Pass	Adjusted
59	NULL	17.993636	Pass	Adjusted
60	NULL	15.997085	Pass	Adjusted
61	NULL	3.722015	Pass	Adjusted
62	NULL	3.223297	Pass	Adjusted
63	NULL	2.812099	Pass	Adjusted
64	NULL	0	Pass	
65	NULL	0	Pass	
66	NULL	0	Pass	

Automated path data point modification

Show all result Show fail result

Point: Parameter

Static

Static

Static

Auto Adjust

All Point

Stand of distance :

Angle adjust :

Manual Adjust

Angle X: Static

Angle Y: Static

Angle Z: Static

Distance : Static

Change robot config New Alignment

Result

Status : **NULL**

Fail Robot Config : Static

Fail Adjust : Static

OK

Cancel

Figure 3.10 The table showing the result of spraying direction adjusting

For certain positions where the automatic adjustment do not work or there is a need to adjust manually, the researcher increased the adjustment by the user in the software. It will come together with the table of result which will pop-up after the user pushes the process path button to make the program perform the process automatically. The manual adjustment will be used when the user needs to spray some positions again.

CHAPTER 4

TOOL PATH IMPROVING FOR SMOOTHLY MOTION

According to collision avoidance and tool path adaptation in chapter 3, although the tool path has been adjusted to avoid the collision, there is still another factor that really affects the coating quality which is the consistency of the spraying gun's moving. We can set the speed of the robot's moving at TCP spot by determining the speed with the unit mm/s in robot command. For the rotating speed of each axis, a robot controller will calculate and control it automatically. Therefore, in the real movement of the robot, even if the speed consistency has been set, the robot cannot perform the exact speed. The speed actually varies depending on the path.

4.1 Robot Operation Testing

4.1.1 Robot Command

After the software tool has finished creating the moving path and adjusting the tool path in some positions, the software will turn the path data into robot command in order to command the robot. The robot command is RAPID language. The order which is used to control robot movement is "Move L". According to the experiment conducted to find the appropriate coating parameters, the result indicates that the TCP Speed should be set at 0.6m/s with the acceptable range between 0.4-0.65m/s. Therefore, we set robot command to make the robot move exactly according to the tool path data at the speed 0.6m/s. A simple move instruction can look like this:

```
MoveL p10, v600, fine, tool0;
```

where:

- **MoveL** is an instruction that moves the robot linearly (in a straight line) from its current position to the specified position.
- **p10** specifies the position that the robot shall move to.
- **v600** specifies that the speed of the robot shall be 600 mm/s.

- **fine** specifies that the robot shall go exactly to the specified position and not cut any corners on its way to the next position.
- **tool0** specifies that it is the mounting flange at the tip of the robot that should move to the specified position.

After that the researcher ordered the robot to run the test. The robot operated movement without spraying. AS a result of the observation of the robot movement in the experiment, we can see that the movement was not smooth and slower than it should be in certain positions. This kind of movement is unacceptable. The reason should be because the automatic controlling of each axis performed by robot controller is independent and still cannot be defined. However, we need to find out the exact speed in order to make an adjustment to get a successful result.

4.2 Define Actual Tool Center Point Speed (TCP Speed)

4.2.1 Tool Center Point Speed Signal

A tool center point normally means a nozzle; however, in this research we consider a tool center point as a deposition point where the flame touches the piece. Therefore, we need to define the distance between the piece and the nozzle to be 65mm as in Figure 4.1. In order to find Tool Center Point Speed (TCP Speed), ABB Robot control unit is able to provide TCP Speed signal. The TCP Speed signal is an analog signal that reflects the speed of the robot's TCP. To read the data of TCP Speed signal, we need to use the ABB test signal viewer as well.

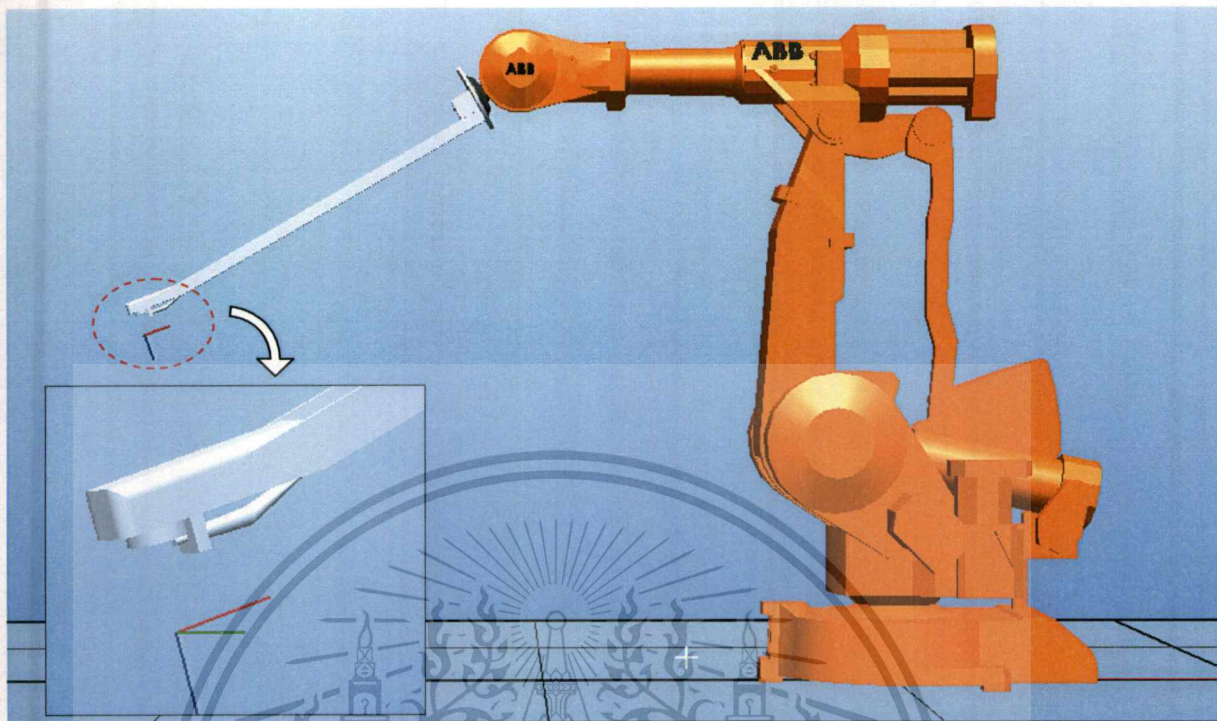


Figure 4.1 Tool Center Point

4.2.2 ABB Test Signal Viewer

The robot controller unit is the part that process robot command, then transform into a signal that automatically controls the robot. Eventually, this part is independent can cannot be interfered. However, we can check in to see the data and the work of the robot including the position, the speed, the acceleration, torque of each axis and also TCP Speed. We can look at several signals using ABB test signal viewer and logging as well. Figure 4.2 show user interface 001 ABB test signal viewer

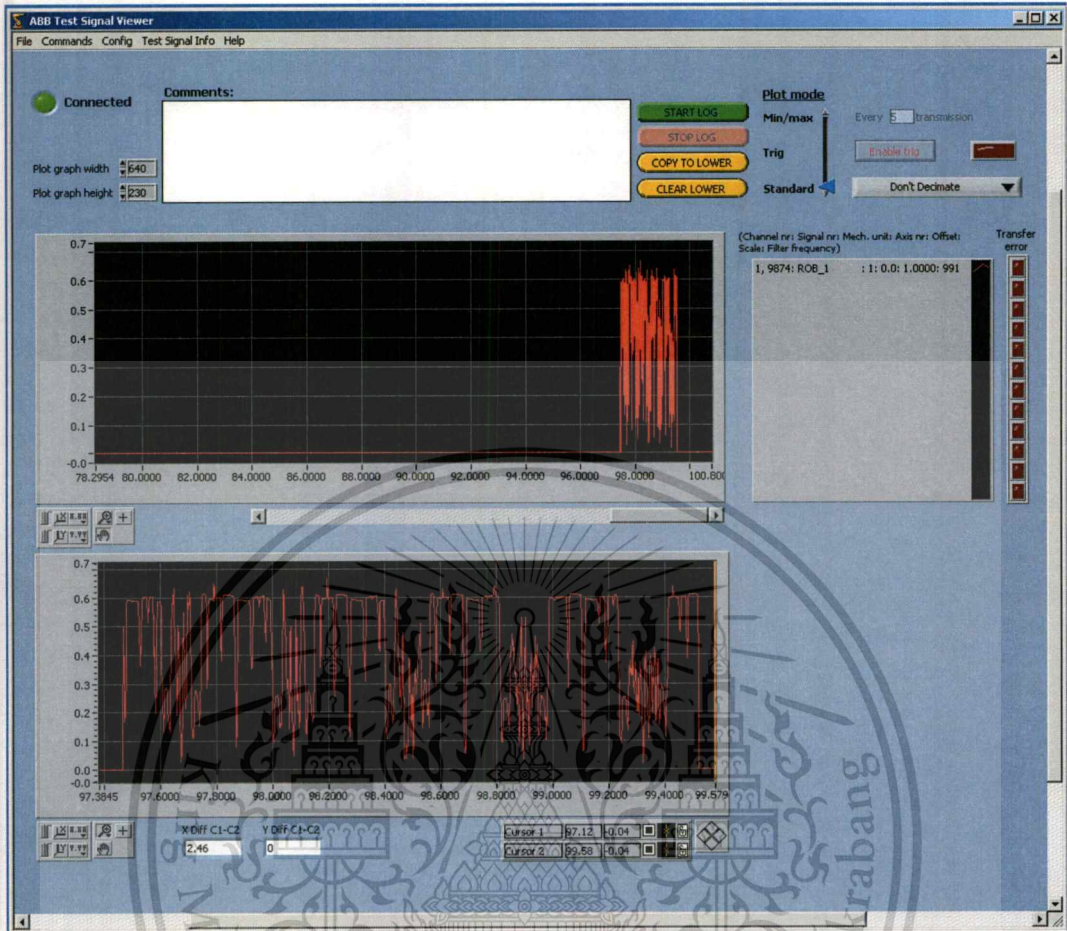


Figure 4.2 ABB test signal viewer

First of all, we need to connect ABB test signal viewer into the robot controller. Then, we need to define test signals to indicate which signal will be read. The define test signal window allows the operator to define 12 Individual channels. Each channel setup consists of six parameters. A signal defining by enter name of Mechanical Unit, then select signal identifier in list or by entering code manually and Select Axis number (1-6). Moreover, we also are able to enter sample time in ms.

4.2.3 Actual TCP Speed Graph

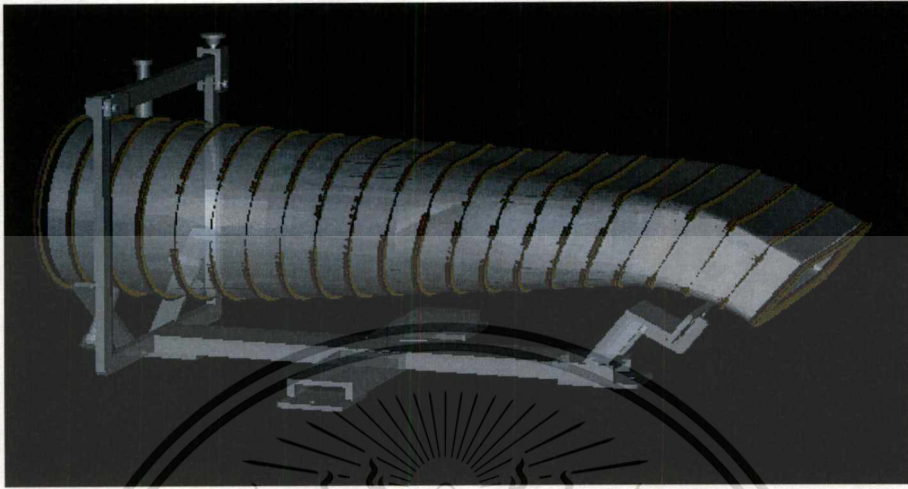


Figure 4.3 Tool path data 8800 point

The researcher defines actual TCP speed according to the real movement of the robot using ABB test signal viewer. In this case, the tool path that the robot is moving along has already been adjusted to avoid the collision from the previous process. However, since the path contains a lot of data as shown in Figure 4.3, even if the TCP speed of the robot command is set at 0.6m/s, the real movement of the robot can be varied into the negative value and below the acceptable range as shown in Figure 4.4.

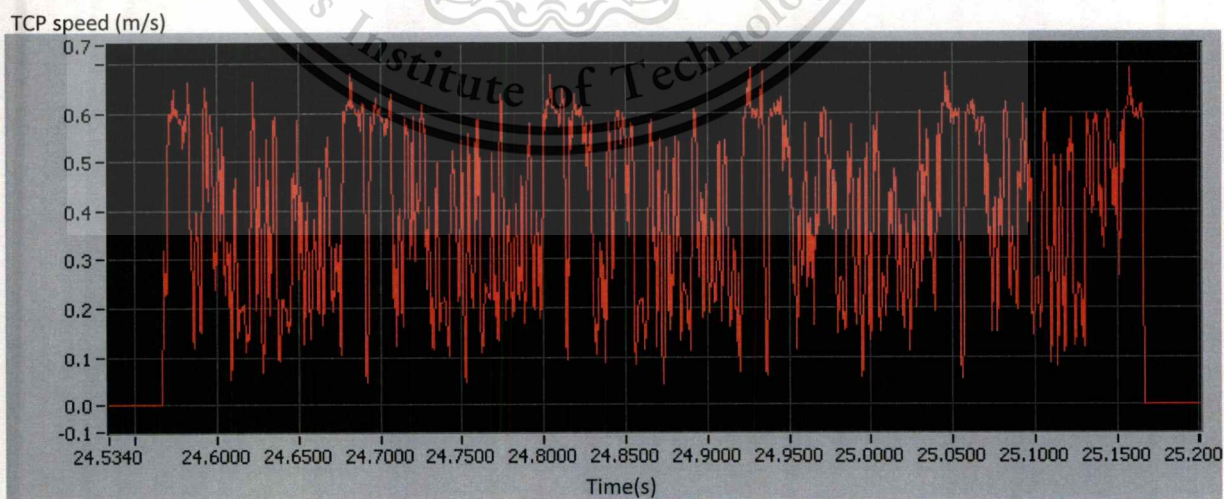


Figure 4.4 TCP speed Graph

4.2.4 TCP Speed Problem Investigation

This section, the researcher uses ABB robot studio in order to help with the analysis. The simulations in ABB robot studio can run the entire robot programs on a virtual controller. Also, with the simulation monitoring functions, the researcher enhances the simulation by adding traces along the TCP movements or alerts triggered by defined speeds or motions. The simulation monitor commands are used to visually detect critical robot movements during simulation by drawing a colored line that follows the TCP. And it displays another color of the trace when any of the alerts exceeds a threshold value.

The researcher brought some data of the tool path to illustrate the idea clearly and easily. Figure 4.5 shows the spraying of the lower part of the transition piece.

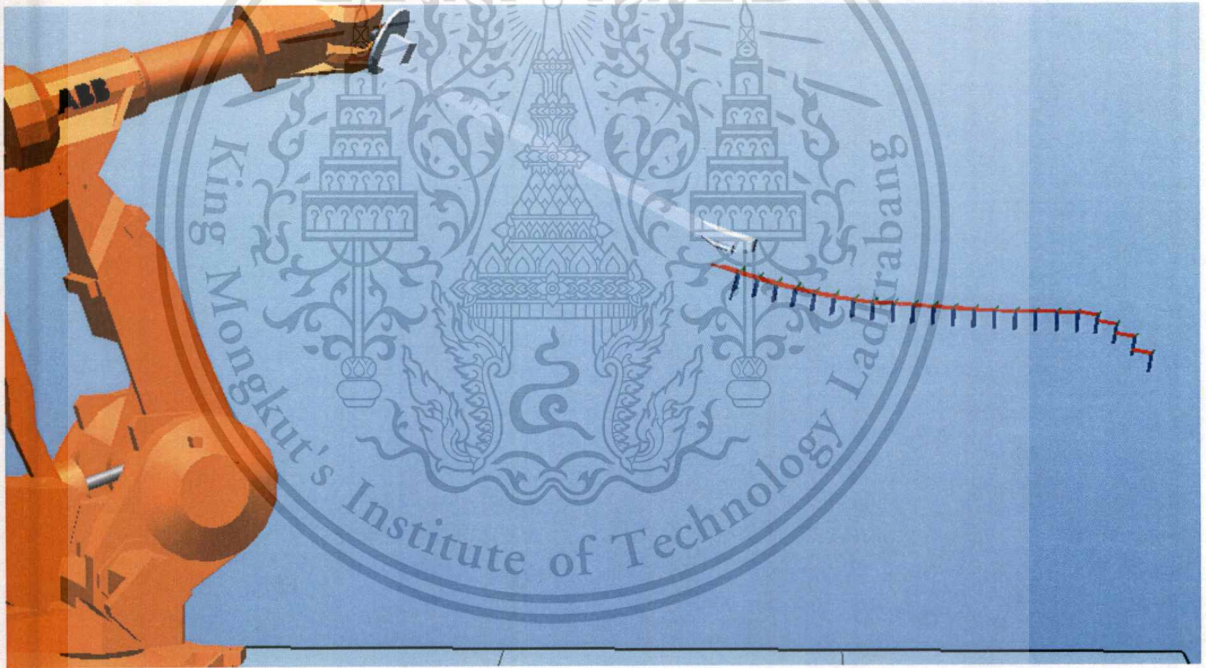


Figure 4.5 Tool path data showing the lower part spraying of the transition piece

The line that can be seen in Figure 4.6 is the movement of the edge of the flame that moves pass the data position of each path in order. This TCP tracing in ABB robot studio function can specify the threshold value for TCP speed alerts. The normal path will appear as white on the line. However, if the movement of the edge of the flame is below 0.4m/s, the color will become black on the line.

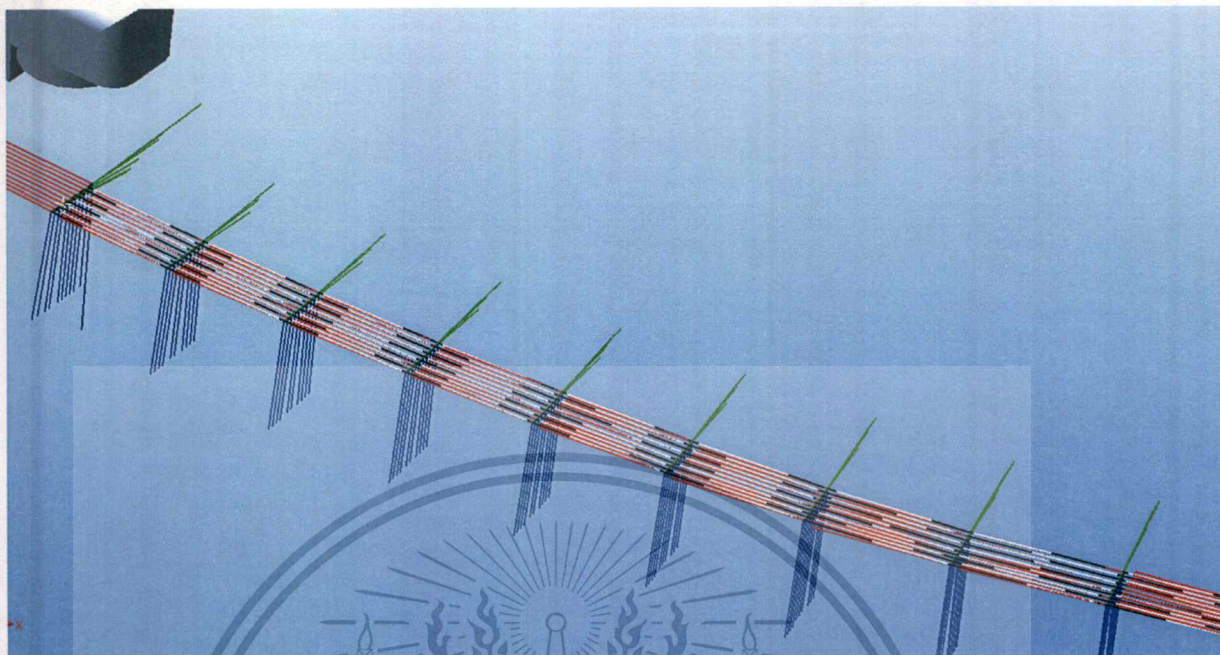


Figure 4.6 Actual path white alerts in the low speed area

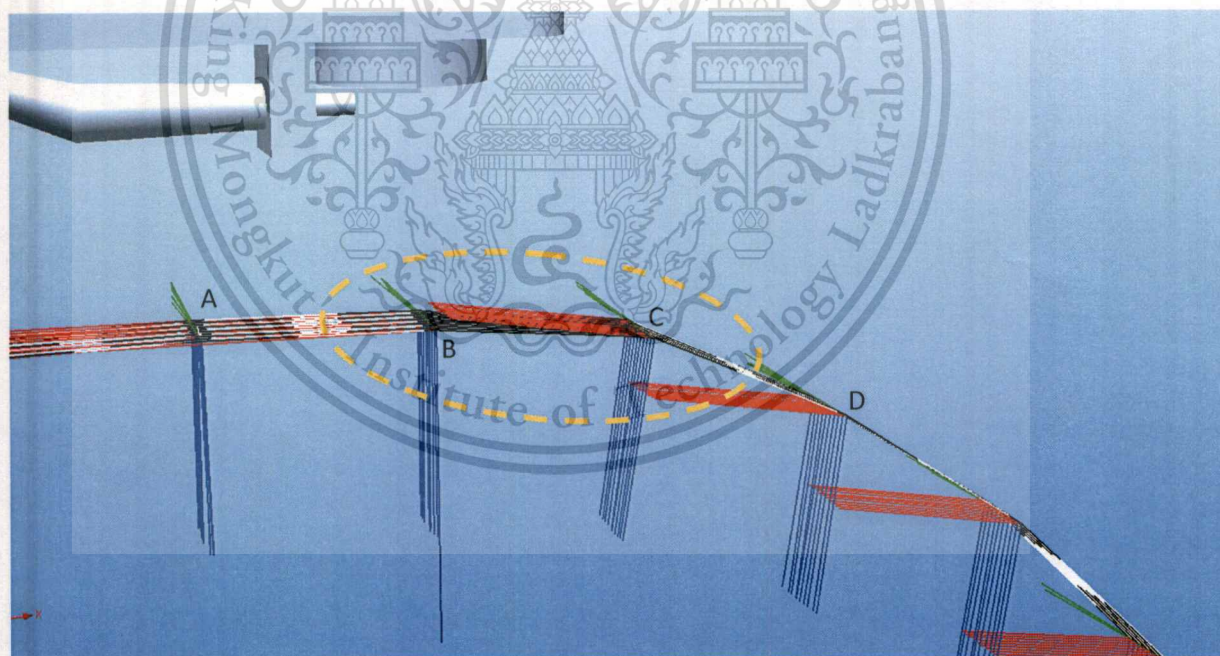


Figure 4.7 Actual path whit alerts in the low speed area (the bending part)

If we look closer, we can see that the part that is slower than 400 mm/s is at the data point and the bending part that contains a lot of variation of orientation. For example, there is a lot of movement back and forth between point B and C as shown in Figure 4.7.

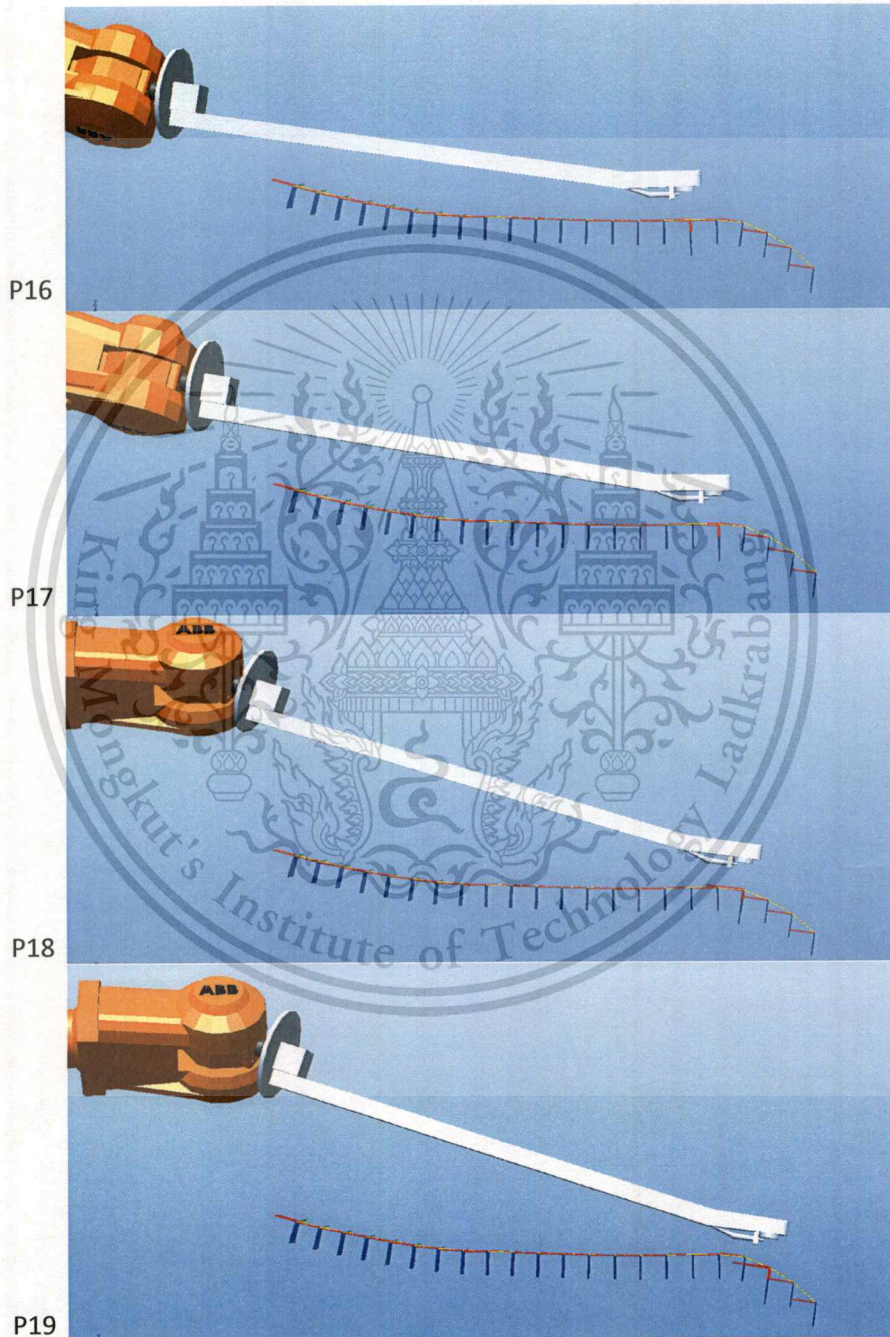


Figure 4.8 The changing pattern of the orientation

Figure 4.8 is an illustration showing the spraying at the positions P16 to P19. It shows the changing pattern of the orientation. When the robot moves through the input path passing through these positions, P16 is in A area, P17 is in B area, P18 is in C area and P19 is in D area respectively as shown in Figure 4.7 (at the bending part)

From P16 to P17, the orientations are very close, so the speed between these two spots is normal. However, from P17 to P18, the orientations are very different. Therefore, the speed between these two spots is slower than normal because the speed is decelerated to adjust the orientation. And then, when the robot passes P18 and gets into P19 position, the speed becomes normal while the output moving is in a similar pattern.

According to the analysis to find the cause of the variation of TCP speed from the acceptable range, we can conclude that it happens because the path contains too much data and certain data is not in the proper position. Moreover, since the robot command has determined the tool to enter the target as fine, robot controller then orders the robot to brake in order to get into every position. Thus, TCP speed is below the acceptable range. In the meantime, the returning of the robot also has low speed. Nonetheless, this part is at the outer part of the transition piece, so it does not have a crucial effect.

In order to adjust the robot motion to be smooth and keeps TCP speed to be as close to the previous set data, we need to consider the curvature to create a new moving path and adjust robot command.

4.3 Work Piece Curvature Consideration and Tool Path Regenerating

In order to solve the unsmooth problem of the robot movement and the actual TCP speed that is lower than the desired point, we need to decrease the point numbers on the tool path to the least possible by deleting the unnecessary parts. This process will prevent the robot from braking several times because of these unnecessary parts and will make this process continue systematically. Therefore, the researcher has added the analysis process for the profile of the transition piece. This process will make us know how many path spots the piece should have and at which position. It should contain least spots as possible but should be able to represent the shape of the piece completely.

4.3.1 Creating a lot of spots along the length of the transition piece

In order to create a new tool path with least spots and the ability to represent the shape of the piece, we need to go back to the beginning of the process in creating the tool path again. The analysis process of the profile starts from sampling the spots on the surface both at the upper and lower parts of the piece. We do this to get the profile data of the piece. In this case, we get sampling from both the upper and lower parts; 100 spots from each as show in Figure 4.9

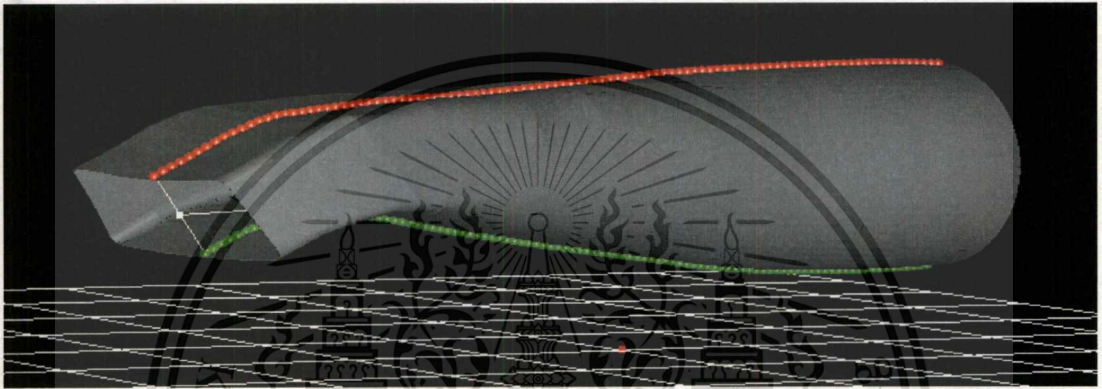


Figure 4.9 Sampling point on the surface both the upper and lower parts of the piece

These spots are on the surface of the piece, so we can use the properties of each position in considering the profile of the transition piece.

4.3.2 Considering all point data and choose the spots

In considering the curvature, we can calculate the changing degree of normal vector. This vector is used in creating spraying direction. If the degree of the normal vector has changed more than 5 degree, we will realize that the spot should have a spot to represent profile of the transition piece. Figure 4.10 shows the character of the normal vector of each sampling point.

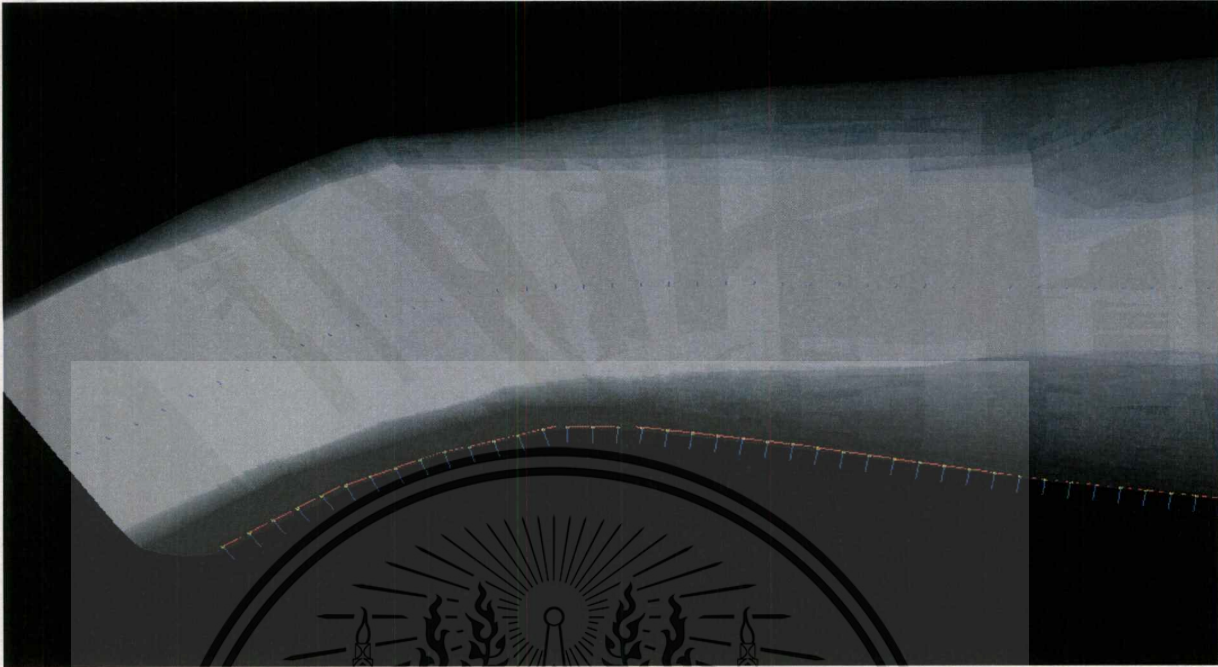


Figure 4.10 Normal vector of each sampling point

We show the data of the normal vector of each sampling point in form of a table and show the changing degrees that we have calculated comparing to the previous referring data. The starting point of the input is the first referring point and is the first point that must have a point data. The tool path program will calculate the changing degrees of the next sampling point of the normal vector. If any positions are found with 5 degree change, the program will set the position to represent tool path and be the new reference spot in calculating the changing degrees.

According to the tool path data selection Table 4.1 and 4.2, both of them show all data of the upper and lower parts of the piece. N_x N_y N_z are the components of the normal vector at that position. Degrees represent the changing degrees that we have calculated comparing to the previous referring data. The colored bar shows the referring data which has the beginning as the first position. The next colored bar is the position that must have path data because of the degree changing of the normal vector that is 5 degrees more than the previous referring data. The last position is also very necessary because it indicates the end of each output. The lower part of the piece must have 9 spots in the positions that the program has chosen as shown with the colored bars. The upper part of the piece must have at least 8 spots.

Table 4.1 Sampling point selection on lower by changing degrees of the normal vector

Order	Position			Vector			Changing Degrees
	X	Y	Z	Nx	Ny	Nz	
1	-483.1	0	127.208	-0.077	0.05	-0.996	0
2	-471.018	0	126.349	-0.065	0.035	-0.997	1.102
3	-459.932	0	125.619	-0.065	0.035	-0.997	1.102
:	:	:	:	:	:	:	:
13	-349.075	0	122.097	0.002	0.043	-0.999	4.548
14	-337.99	0	122.176	0.002	0.043	-0.999	4.548
15	-326.904	0	122.247	0.009	0.071	-0.997	5.075
16	-315.818	0	122.302	0.009	0.071	-0.997	0.000
17	-304.733	0	122.481	0.024	0.034	-0.999	2.291
:	:	:	:	:	:	:	:
25	-216.047	0	125.751	0.054	0.055	-0.997	2.737
26	-204.962	0	126.274	0.054	0.055	-0.997	2.737
27	-193.876	0	127.146	0.08	0.017	-0.997	5.113
28	-182.79	0	128.112	0.08	0.017	-0.997	0.000
:	:	:	:	:	:	:	:
35	-105.191	0	137.006	0.143	0.011	-0.99	3.647
36	-94.105	0	138.576	0.171	0.019	-0.985	5.261
37	-83.019	0	140.646	0.171	0.019	-0.985	0.000
38	-71.934	0	142.716	0.171	0.019	-0.985	0.000
:	:	:	:	:	:	:	:
82	415.836	0	232.406	0.173	0.057	-0.983	2.184
83	426.922	0	234.364	0.166	0.059	-0.984	2.311
84	438.007	0	235.234	0.056	0.052	-0.997	6.894
85	449.093	0	235.975	0.055	0.05	-0.997	0.128
86	460.179	0	236.572	0.051	0.058	-0.997	0.448
87	471.264	0	235.262	-0.243	0.052	-0.969	17.269
88	482.35	0	232.464	-0.254	0.059	-0.965	0.780
89	493.436	0	229.653	-0.258	0.054	-0.965	0.897
90	504.521	0	226.725	-0.242	0.035	-0.97	0.977
91	515.607	0	224.199	-0.242	0.035	-0.97	0.977
92	526.693	0	220.104	-0.365	0.044	-0.93	7.356
93	537.778	0	215.469	-0.365	0.044	-0.93	0.000
94	548.864	0	211.023	-0.364	0.054	-0.93	0.576
95	559.95	0	206.631	-0.364	0.054	-0.93	0.576
96	571.035	0	200.773	-0.524	0.061	-0.85	10.256
97	582.121	0	193.943	-0.529	0.065	-0.846	0.432
98	593.207	0	187.104	-0.526	0.052	-0.849	0.531
99	604.292	0	180.329	-0.53	0.057	-0.846	0.472
100	616.225	0.001	172.868	-0.53	0.049	-0.846	0.801

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Table 4.2 Sampling point selection on upper by changing degrees of the normal vector

Order	Position			vector			Changing degrees
	X	Y	Z	Nx	Ny	Nz	
1	-467.045	0	468.3	-0.019	0.087	0.996	0
2	-467.045	0	468.3	-0.019	0.087	0.996	2.689
3	-455.245	0	468.485	-0.009	0.07	0.998	2.076
:				:			:
14	-325.445	0	467.313	0.035	0.065	0.997	4.061
15	-313.645	0	466.902	0.035	0.065	0.997	4.061
16	-301.845	0	466.456	0.042	0.09	0.995	5.060
17	-290.045	0	465.93	0.044	0.055	0.998	2.015
18	-278.245	0	465.401	0.044	0.055	0.998	2.015
:				:			:
35	-77.644	0	453.859	0.071	0.03	0.997	3.821
36	-65.844	0	452.97	0.071	0.03	0.997	3.821
37	-54.044	0	452.04	0.072	0.001	0.997	5.386
38	-42.244	0	451.106	0.072	0.001	0.997	0.000
39	-30.444	0	449.938	0.117	0.002	0.993	2.590
:				:			:
75	394.357	0	405.109	0.115	-0.053	0.992	3.967
76	406.157	0	403.654	0.115	-0.053	0.992	3.967
77	417.957	0	402.093	0.148	-0.044	0.988	5.089
78	429.757	0	400.333	0.148	-0.044	0.988	0.000
79	441.557	0	398.573	0.148	-0.044	0.988	0.000
:				:			:
84	500.557	0	389.609	0.151	-0.035	0.988	0.544
85	512.357	0	387.844	0.153	-0.041	0.987	0.338
86	524.157	0	385.839	0.332	-0.04	0.943	10.869
87	535.957	0	381.601	0.333	-0.028	0.943	0.690
88	547.757	0	377.45	0.334	-0.033	0.942	0.420
89	559.557	0	372.162	0.458	-0.036	0.888	7.885
90	571.357	0	366.034	0.457	-0.029	0.889	0.409
91	583.157	0	360.043	0.458	-0.038	0.888	0.115
92	594.958	0	354.054	0.457	-0.029	0.889	0.409
93	606.758	0	346.197	0.558	-0.026	0.829	6.683
94	618.558	0	338.253	0.559	-0.03	0.829	0.233
95	630.358	0	330.316	0.559	-0.03	0.829	0.233
96	642.158	0	322.666	0.518	-0.022	0.855	2.744
97	653.958	0	315.542	0.516	-0.04	0.856	2.971
98	665.758	0	308.419	0.516	-0.04	0.856	2.971
99	677.558	0	301.304	0.515	-0.052	0.856	3.269
100	690.214	0	293.643	0.515	-0.05	0.856	3.218

4.3.3 Creating a new tool path

We can create a new tool path with the result of the position choosing. However, in order to create a new tool path automatically referring from the cutting plane, we need to determine 9 spots for both the upper and lower parts. Therefore, the new tool part which has only the necessary spots is very different from the previous tool part as shown in Figure 4.11 with the new tool path considering from the bending part as shown in Figure 4.12. When we consider a specific path, we can see that we will get a lot better path. Even if the whole picture of the new tool path might look odd since the cross section plane is not arranged neatly in straight line pattern.

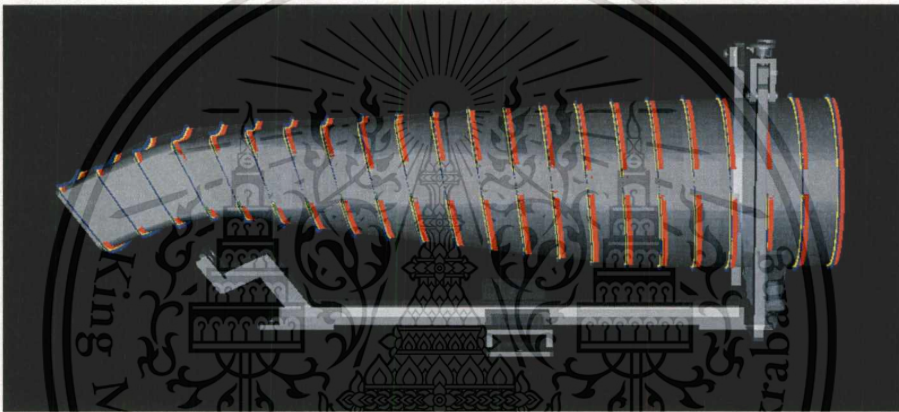


Figure 4.11 Tool path (old version)

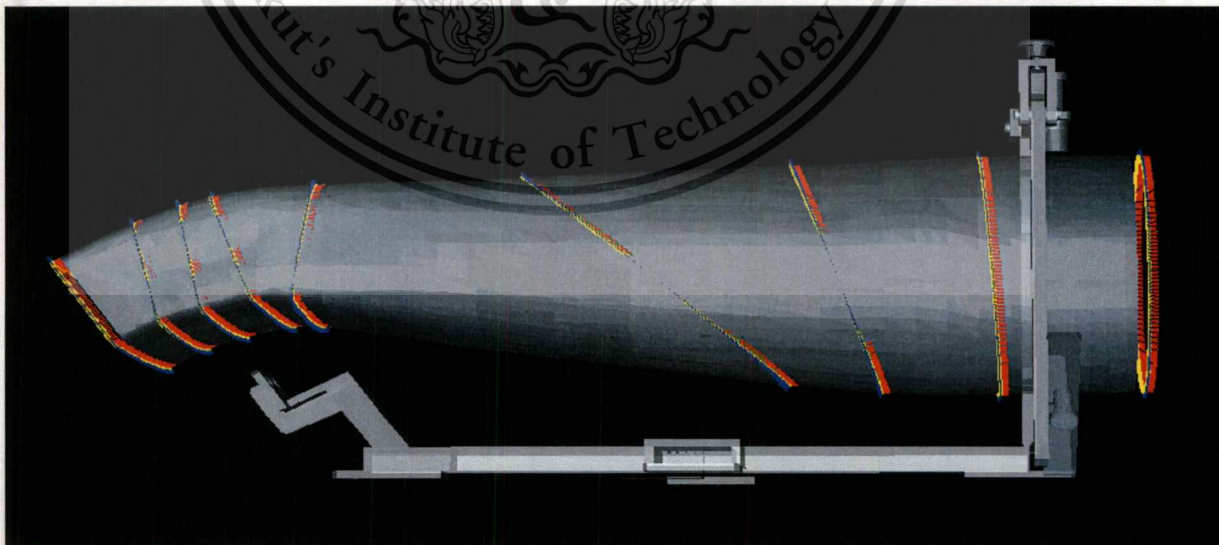


Figure 4.12 New tool path (considering from the bending)

After that we can take the new tool path to undergo the process of Collision Avoidance and Tool Path Adaptation again as well.

4.4 Robot Command Modification

4.4.1 Robot Move Instruction Usage

Robot command modification in the move instruction part is another part that will make the movement smoother. "MoveL" is used to move the tool center point (TCP) linearly to a given destination and can also be used to reorientate the tool when the TCP is to remain stationary. Normally the command that is used is:

```
MoveL p10, v600, fine, tool0;
```

Arguments of this move instruction is: *MoveL ToPoint Speed Zone Tool;*

ToPoint

ToPoint is the destination point of the robot and external axes. It is defined as a named position or stored directly in the instruction.

Speed

It is defined by 'speeddata'. The 'speeddata' that applies to movements. Speed data defines the velocity for the tool center point and the tool reorientation.

Zone

It is defined by 'zonedata' which specifies a corner zone for the movement. Zone data describes the size of the generated corner path.

Tool

It specifies the tool that the robot is using when the robot moves. The tool center point is the point moved to the specified destination position.

Program execution of the robot and external units are moved to the destination position as follows:

- The TCP of the tool is moved linearly at constant programmed velocity.
- The tool is reoriented at equal intervals along the path.

If it is not possible to attain the programmed velocity for the reorientation or for the external axes then the velocity of the TCP will be reduced.

A corner path is usually generated when movement is transferred to the next section of a path. If a stop point is specified in the zone data then program execution only continues when the robot and external axes have reached the appropriate position.

4.4.2 Zone for Robot Movement

Zone is used to specify how a position is to be terminated, i.e. how close to the programmed position the axes must be before moving towards the next position. A position can be terminated either in the form of a stop point or a fly-by point.

A stop point means that the robot and external axes must reach the specified position (stand still) before program execution continues with the next instruction. It is also possible to define stop points other than the predefined fine. The stop criteria, that tell if the robot is considered to have reached the point, can be manipulated using the stopping point data.

A fly-by point means that the programmed position is never attained. Instead, the direction of motion is changed before the position is reached. Two different zones (ranges) can be defined for each position:

- The zone for the TCP path.
- The extended zone for reorientation of the tool and for external axes.

Zones function is the same during joint movement, but the zone size may differ somewhat from the one programmed. The zone size cannot be larger than half the distance to the closest position (forwards or backwards). If a larger zone is specified, the robot automatically reduces it.

The zone for the TCP path, A corner path (parabola) is generated as soon as the edge of the zone is reached (see figure 4.13).

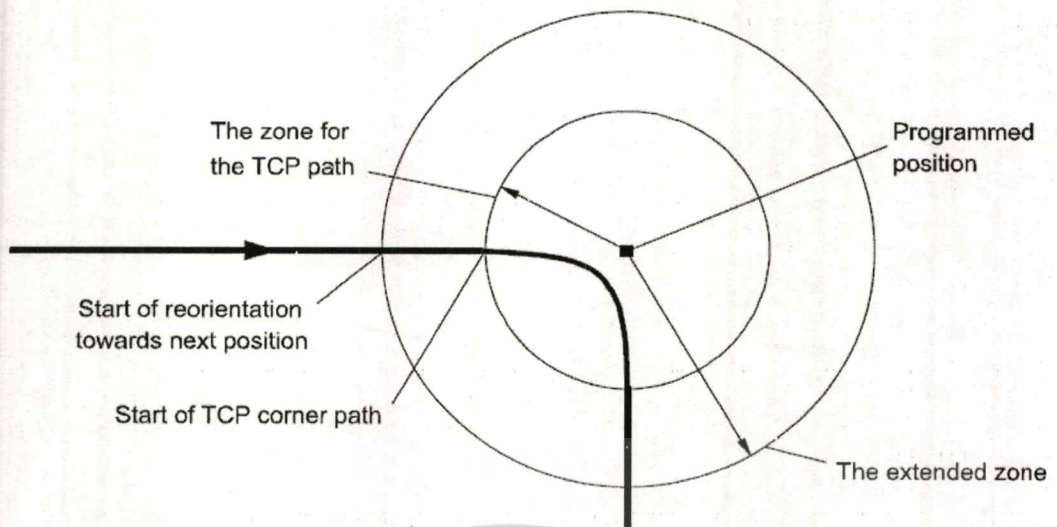


Figure 4.13 The zone for the TCP path

The zone for reorientation of the tool, reorientation starts as soon as the TCP reaches the extended zone. The tool is reoriented in such a way that the orientation is the same leaving the zone as it would have been in the same position if stop points had been programmed. Reorientation will be smoother if the zone size is increased, and there is less of a risk of having to reduce the velocity to carry out the reorientation. The following figure 4.14 a) shows three programmed positions, the last with different tool orientation. b) Shows what program execution would look like if all positions were stop points. c) Shows what program execution would look like if the middle position was a fly-by point.

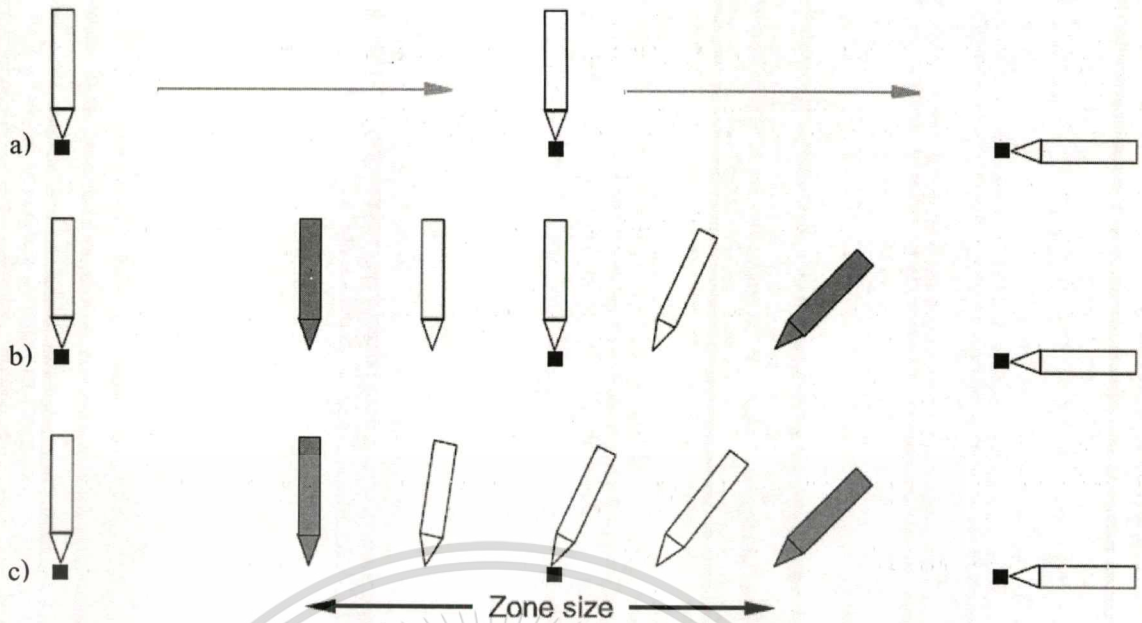


Figure 4.14 The zone for reorientation of the tool

a) three programmed positions, the last with different tool orientation.

b) program execution if all positions are stop points.

c) program execution if the middle position is a fly-by point.

4.4.3 Path Zone Modification

Zone is the thing that we will adjust. At first, we have set the tool path data to be fly-by point and use the command as `MoveL p10, v600, z200, tool0;`

The z200 determines the TCP Path zone to be 200mm while the Orientation zone to be 300mm. However, in changing the former data point from stop points to be fly-by point and expand the ranges in order to allow the movement to pass without attained. This process will allow the robot control to calculate and program automatically by itself while we must monitor to make ensure the desired result.

4.4.4 Examining the result of the zone adjusting

When we adjust the zone value to be 200, the movement will be smoother, but will create an undesired result. The tool path will be moved as well because data position of the path is changed to fly-by point with TCP Path zone as big as 200mm. The change of the TCP Path has an effect on

spraying distance. Therefore, we need to review actual tool path again to test whether the spraying distance is still in the acceptable range.

As well as TCP Speed Problem Investigation, in order to illustrate a clear picture that is easy to understand, we have selected only the tool path data for the spraying of the lower part of the transition piece to make a consideration and comparison in Figure 4.15. It shows that the new tool path will contain only the tool path data point in the appropriate positions.

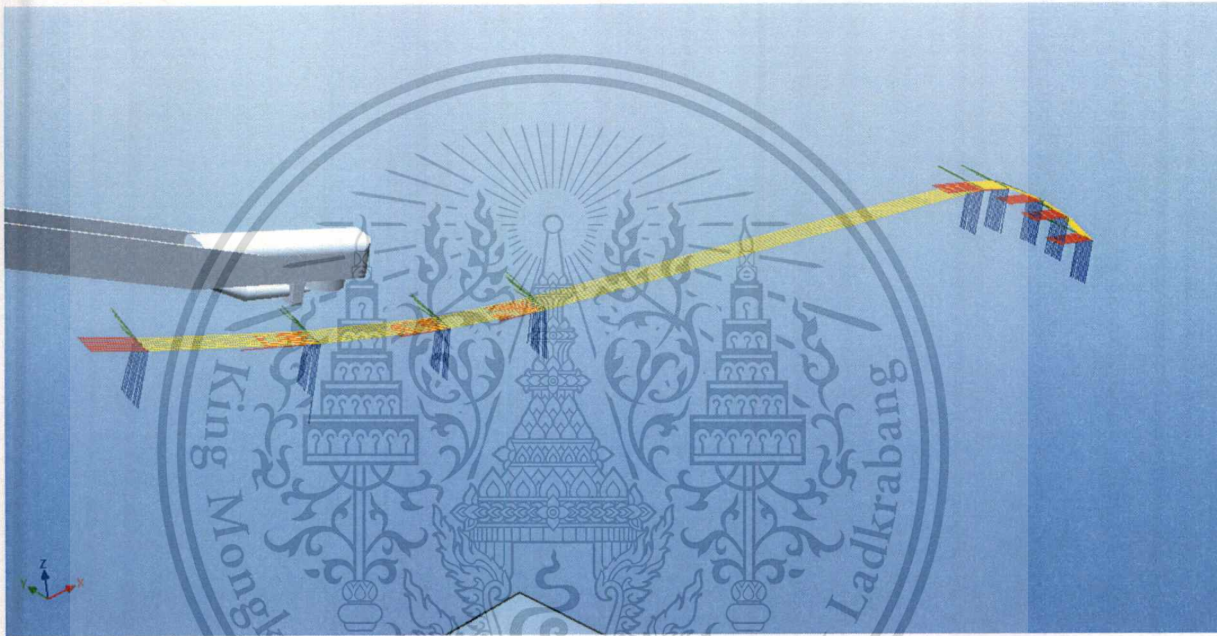


Figure 4.15 The new tool path

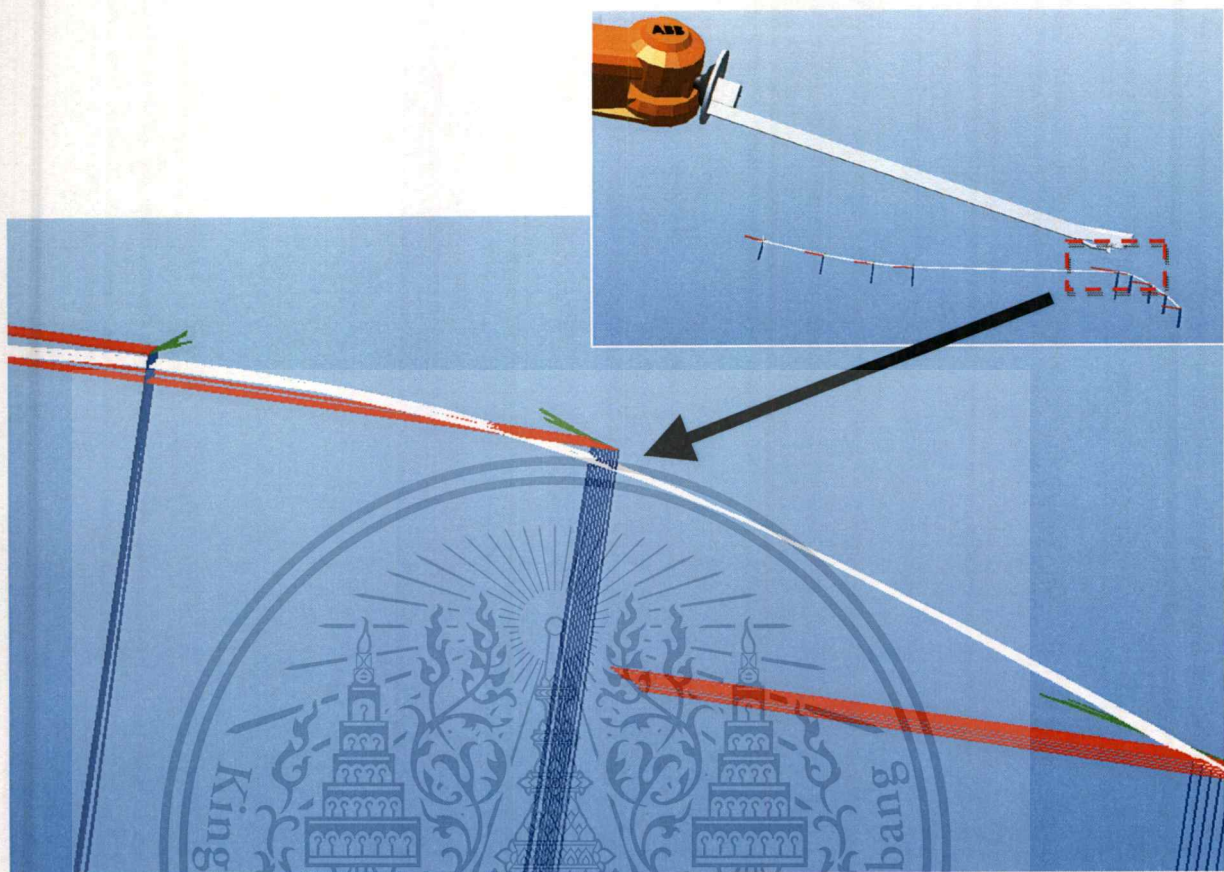


Figure 4.16 Spraying distance error

The point with most errors will cause the spraying distance to change with 1mm decrease. However, the spraying distance error remains in the acceptable range and has a very little effect to the coating quality. According to the sample shown in this thesis, the adjustment of the robot movement by using the process called Work Piece Curvature Consideration and Tool Path Regenerating together with the process called Path Zone Modification and Examining the result of the zone adjusting have created a new tool path which is controlled by the proper and desirable robot command. For any other spraying cases, if the actual tool path has more error than the acceptable range, we are able to reduce the zone value in certain positions.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Effects of Collision Avoidance and Tool Path Adaptation

The result of Collision Avoidance and Tool Path Adaptation for the case study: spray coating the transition piece model 701F. Most of the spray angles have been modified which constrained by the acceptable criteria. As a result, the robot can successfully perform the spraying within the transition piece, going along the length of the piece and returning back without collision. Figure 5.1 show robot moves on collision free tool path which capture from robot simulation.

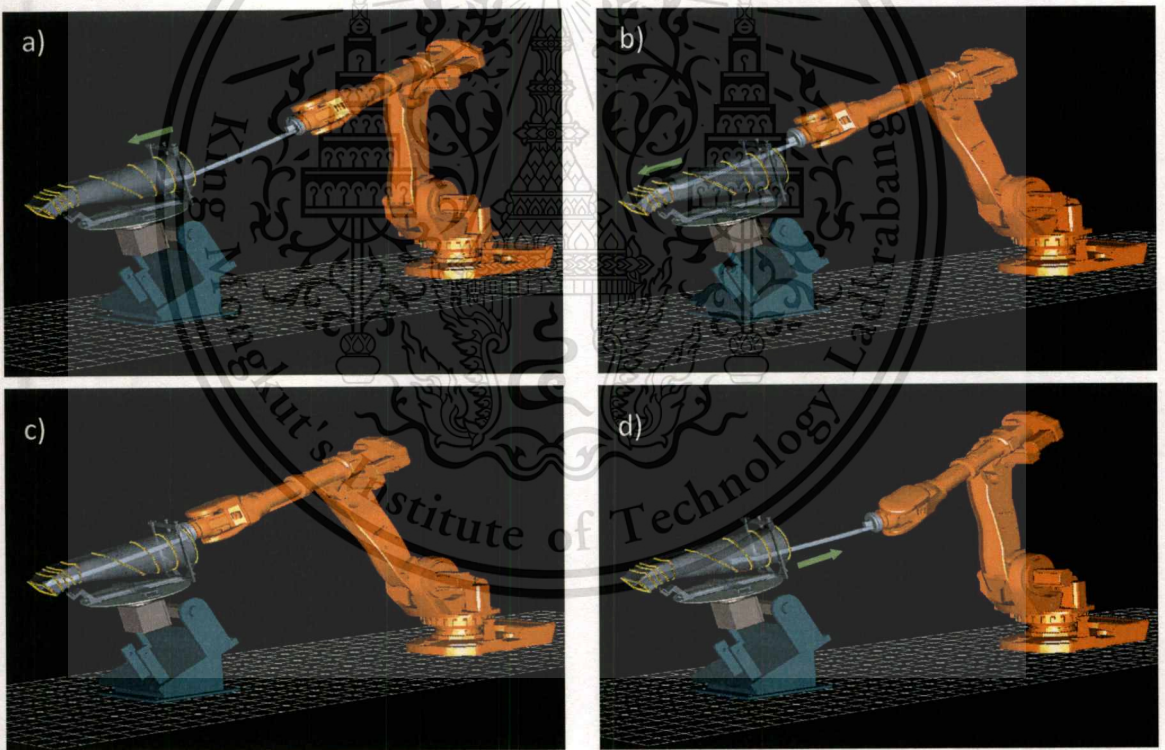


Figure 5.1 Root moving on Collision Free Tool Path in Robot Simulation

The success of Tool Path Adaptation will vary depending on each tool path which is automatically created. As a result of the success of tool path adaptation to avoid collision of spray coating of the transition piece model 701F, we have concluded the result from the final tool path

derived from the choosing of path data point as shown in Figure 5.1 which is a new tool path getting from curving consideration.

There are 3,600 path data point altogether. From all these points, there are only 1,750 points that contain simulation software detect collision. After we apply Automated Tool Path Adaptation, we can create 1,327 points without collision which is 75.8% of the total collision points.

Table 5.1 The tool path adaptation result of transition piece model 701F

model 701f/ The new tool path from Work Piece Curvature Consideration and Tool Path Regenerating				
Tool Path Point	Collision	Adjusted	Success Rate	Auto Adjust Fail
3600	1750	1327	75.8 %	423

Moreover, we have presented the result of another case study in order to illustrate the performance of tool path adaptation function. Model 9f has been used in the case study as shown in Figure 5.2 by concluding the result from original tool path from automated generating

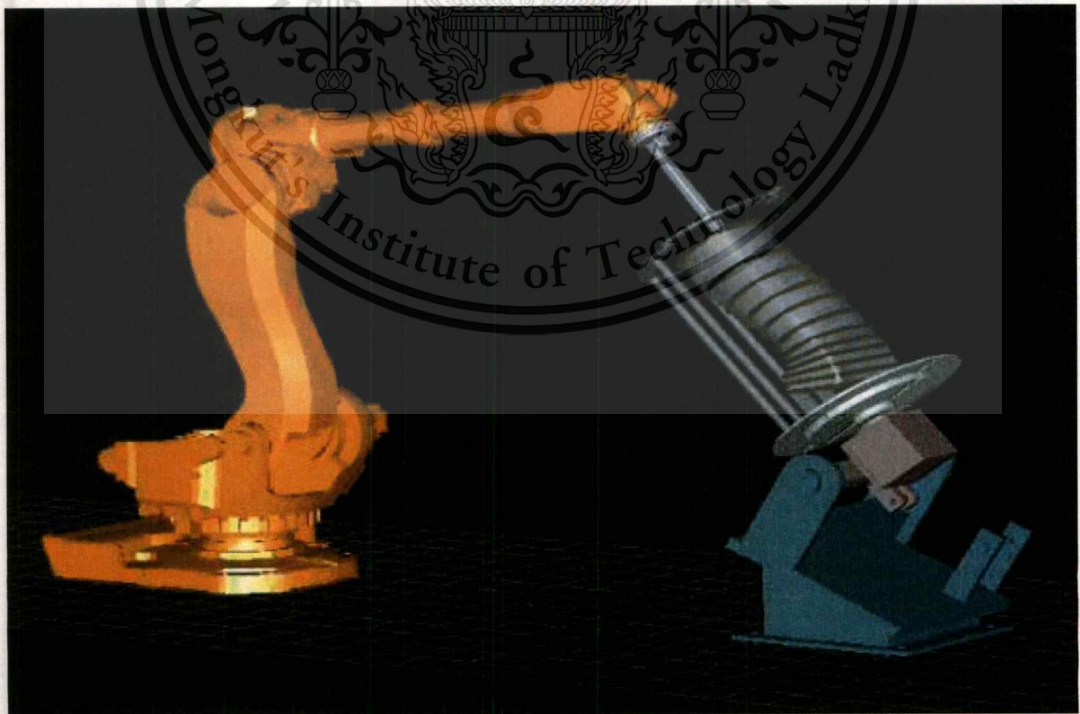


Figure 5.2 The robot working on Transition Piece Model 9FA

The success of Tool Path Adaptation from simulations process shows that within the 4,800 path data positions, there are 2,043 positions being detected with collision. This algorithm can completely avoid collision at 1,917 positions which is 93.8% of all the possible collision positions.

Table 5.2 The tool path adaptation result of transition piece model 9F

model 9f / original tool path from automated generating				
Tool Path Point	Collision	Adjusted	Success Rate	Auto Adjust Fail
4800	2043	1916	93.7%	127

5.2 Effects of Robot Motion Improving

In each robot plasma spray operation, the robot needs to insert the spraying tool back and forth for so many times. The robot needs to move in the same pattern for each time; therefore, TCP speed Graph will demonstrate only one range of the movement.

5.2.1 The Effects from Path Zone Modification

In order to show the Effects from Path Zone Modification clearly, we apply the same tool path as in figure 4.3 which consists of data 8800 point and robot command. We set TCP speed to be at 0.6m/s but change the stop point to be fly-by point by setting Zone as z200. TCP speed Graph shown in figure 5.x is the movement from the starting point and continues to move back and forth for five times as in figure 4.4. The yellow blanket shown in Figure 5.x marks one round of movement.

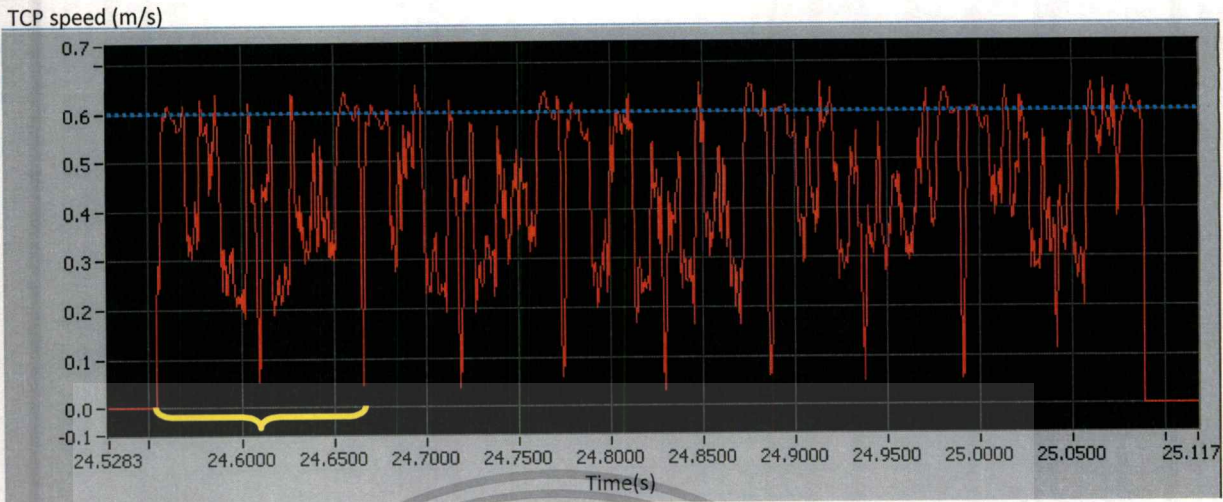


Figure 5.3 TCP speed Graph when Zone is changed to 200

When comparing TCP speed Graph between figure 4.4 and figure 5.3, we can see a clear difference from the previous position with high fluctuation and value below acceptable range almost along the movement where TCP speed is set as 0.6m/s (blue dash line). Resulting tool path from Path Zone Modification process is the tool path containing the range that allows robot controller to be able to automatically adjust spraying orientations to be suitable for each position. Also, this process controls the robot to move along tool path data point without stopping in order to approach to the point. In Figure 5.3, we can see that actual TCP speed has less fluctuation and has out of spec parts a lot less. However, it is not applicable since there is the need for the TCP speed within the coating area to be keep above 0.4m/s

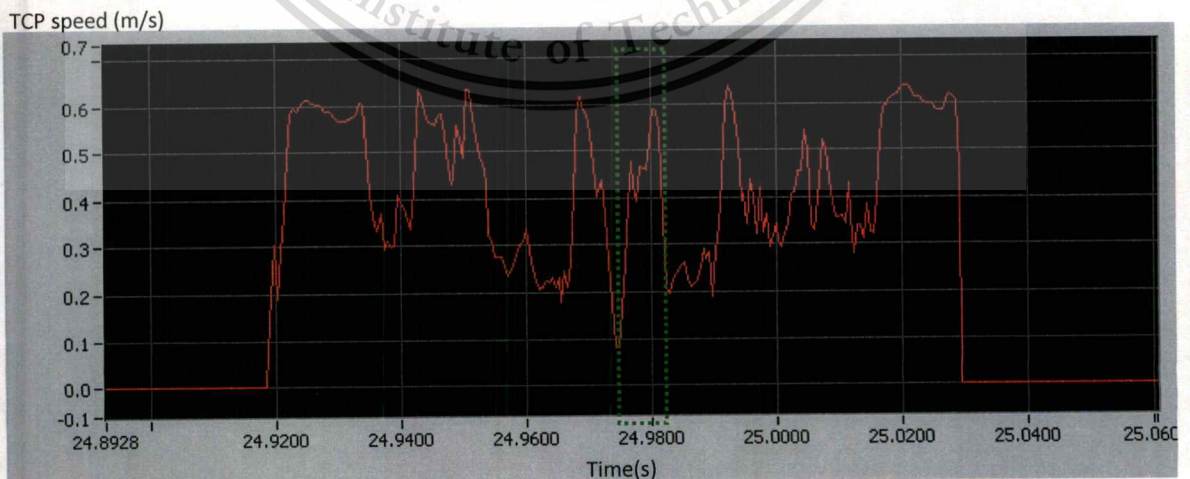


Figure 5.4 Single round TCP speed Graph when Zone is changed to 200

When we expand TCP speed Graph to see a single round of movement, we can see unsolicited decreasing of TCP speed clear as in Figure 5.4. The slowing down of the TCP speed inside the green dot happens during the reverse of the robot which is outside the coating area. Therefore, even if the TCP speed is below 0.4m/s, it does not affect the coating quality.

5.2.2 The Effects from Tool Path Regenerating By Curvature Consideration

Path Zone Modification can adjust robot motion to be better only at a certain level. However, if we apply both techniques: Path Zone Modification and Tool Path Regenerating by Curvature Consideration, they can create the best movement. The TCP Speed will change the previous set values for just a little. The new tool path from the Curvature Consideration as show in Figure 5.5 is a perfect tool path and has the best performance in spray coating the transition piece model 701f. The piece is regenerated from the software concluding the function of movement adaptation and automatic collision avoidance together which is the finding of this research.

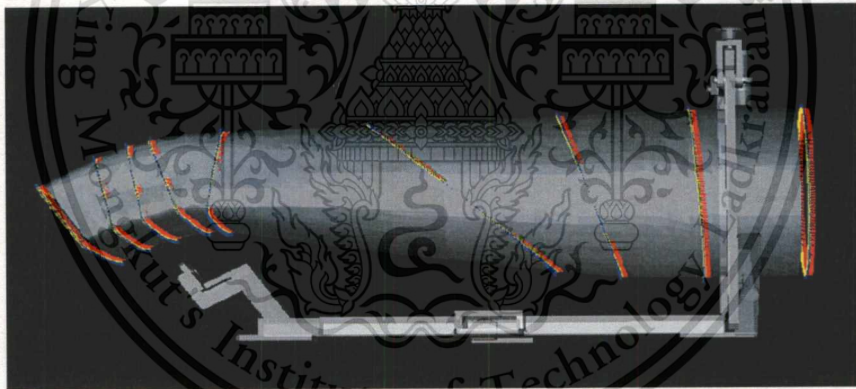


Figure 5.5 The new tool path from the Curvature Consideration

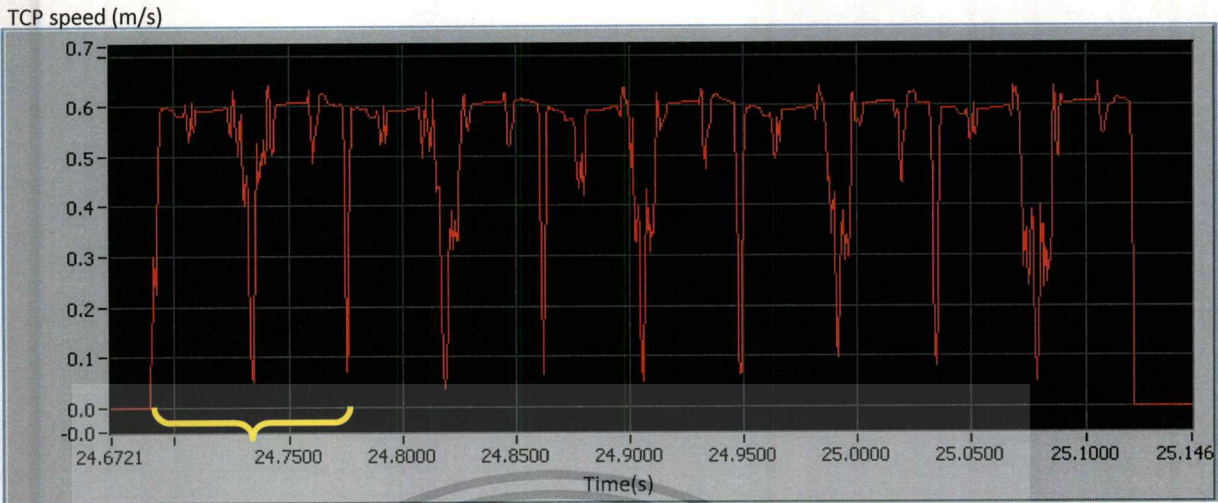


Figure 5.6 TCP speed Graph of the new tool path from the Curvature Consideration and Zone Modification

TCP speed Graph of the new tool path from the Curvature Consideration and Zone Modification in Figure 5.6 has a specific qualification. From the beginning of the movement, the TCP speed will increase from 0 to about 0.6m/s. Then, this new tool path is able to maintain the TCP speed in the part on the coating surface. The value varies within acceptable range. At the reverse part of the Tool path, the TCP speed still decreases as before. However, the movement of the plasma flame outside the work piece will not affect coating quality as mentioned earlier. The detail of the TCP speed Graph can be seen more clearly from the larger figure of single round TCP speed Graph in Figure 5.7.

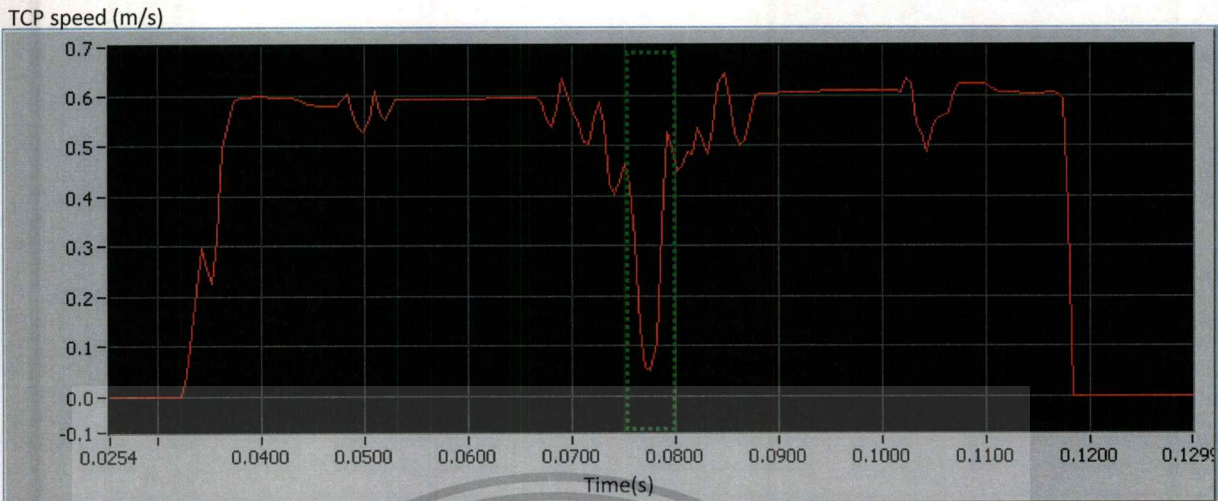


Figure 5.7 Single round TCP speed Graph of the new tool path from Curvature Consideration and Zone Modification

5.3 Manual Tool Path Modification for some difficult and point

For this software Version, the researchers have added software that enables manual adjustment of the spraying gun by the user. When the table showing the result of automatic spraying gun adjustment has popped up after the user chose “process path” button, allowing the software to process the automatic adjustment, manual adjustment can be performed in some cases when the user would like to adjust the spraying of some parts again or when the automatic adjustment did not give a desired result.

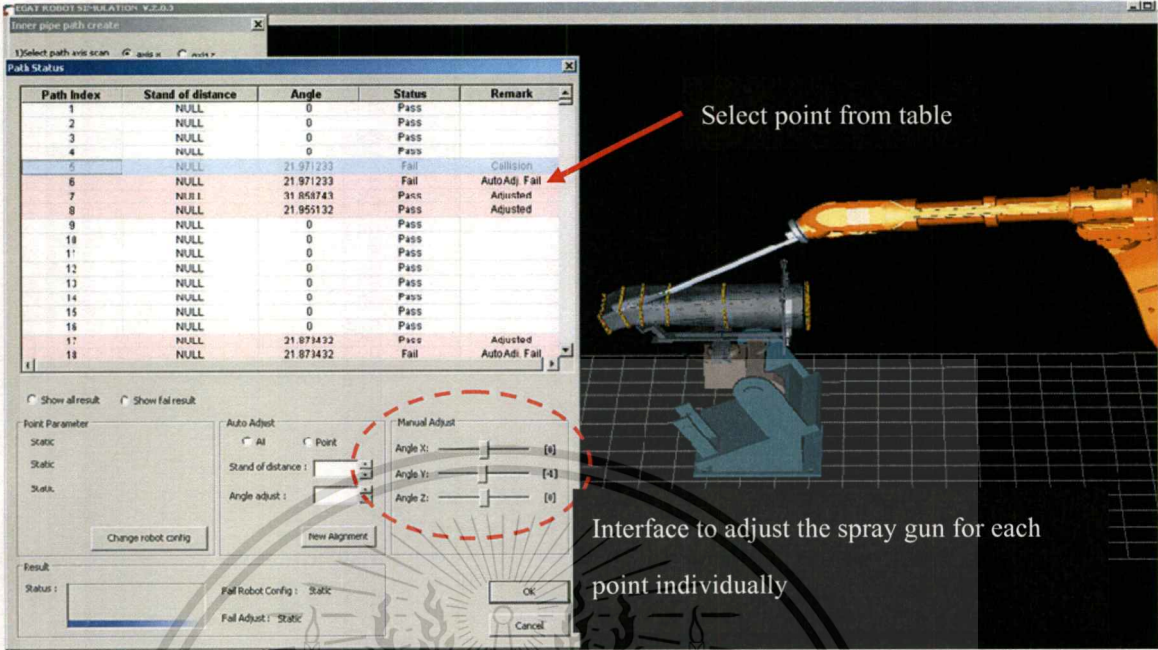


Figure 5.8 Interface to adjust the spray gun for each point individually

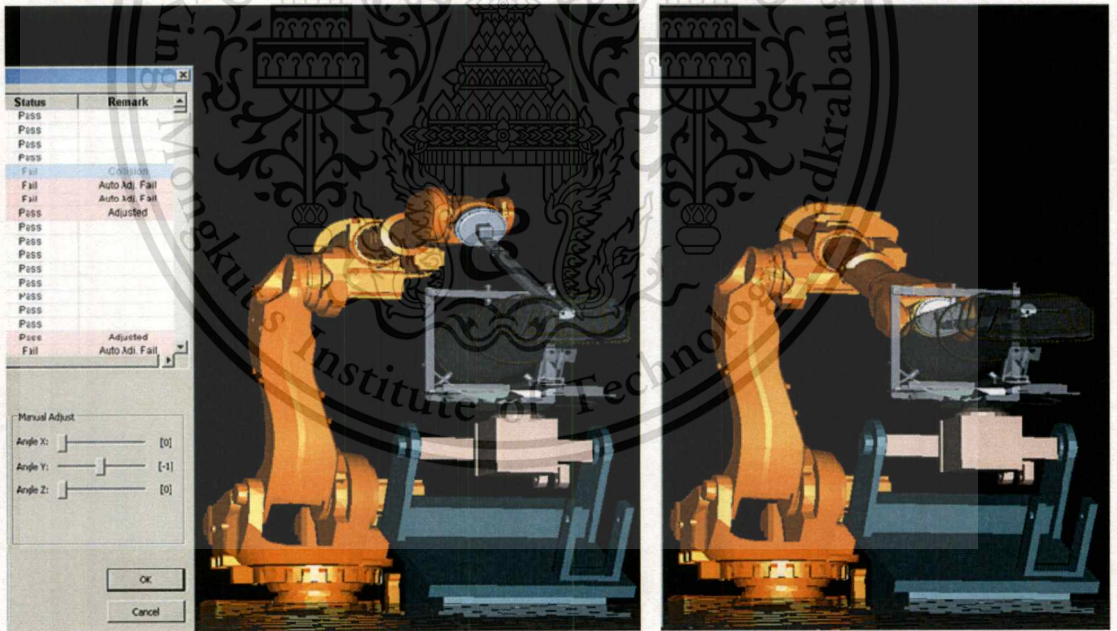


Figure 5.9 The spraying gun adjustment at a position on the table showing spraying path of the user

5.4 The Comparison between the Developed Software and Commercial Software.

The software tool, developed by the Automation Lab, is based on C++ and OpenGL Library. The OpenGL is a Computer Graphic Library which is a free and open source for public use. The library allows the developed software to be used in running effectively with quick response. Moreover, since the software was developed by the Automation Lab, useful add-on features can be created easily. As a result, the outcome software can be expanded for further spraying application, for example, blasting spray, Arc Wire Spray and etc.

The developed software tool is able to load CAD Model of the transition piece instantly. The work file needs to be in STL format. Also, if the file can show the 3D cad of the surface of the transition piece, the process will be more convenient and much easier. In case that the 3D CAD does not exist, a scanner, such as, Computer Coordinate Measuring Machine (CMM) can be used to scan the transition piece or other commercial software can be another choice in creating the 3D CAD file.

In order to create a tool path to respond the user's need and to be suitable with transition piece with smooth coating, several processes need to be performed. If these processes are not divided and arranged appropriately, they can confuse the software user. Specific software is designed to control the movement of the robot for spraying the inner surface of a tubular piece. As in our case study, the software creates the tool path according to the 3D surface of the piece determined by the user. Additionally, within the developed software, several features can be found. To illustrate, there is a feature dealing with the spraying angle adaptation to automatically avoid collision. Also, there is a feature which is able to simulate robot configuration before the robot operation.

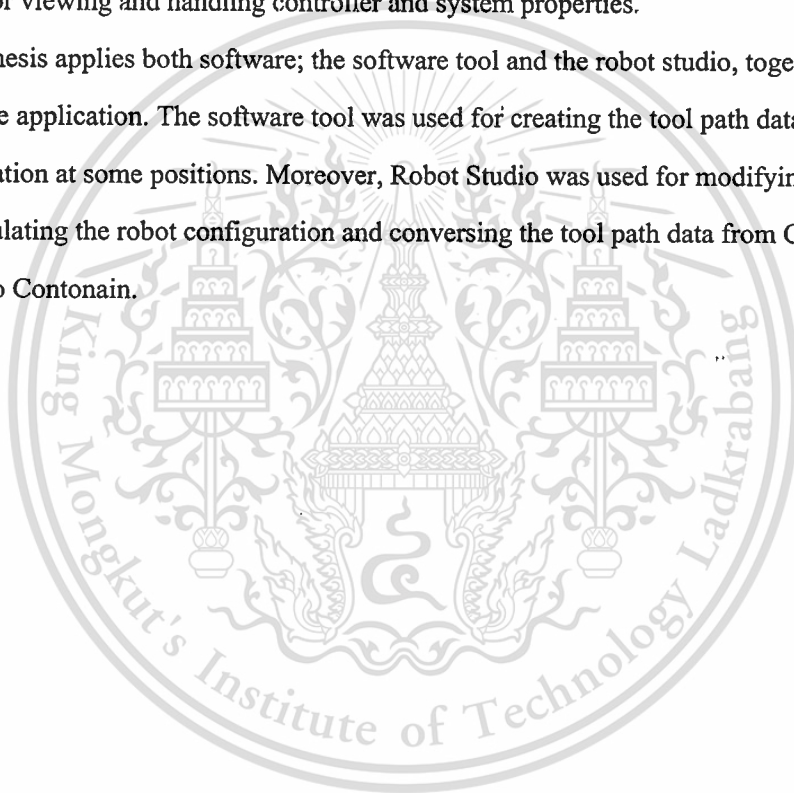
Robot Studio Online is a PC software with which you work with robots, as a complement to working from the Flex Pendant. Robot Studio Online is optimized for text based programming (suitable for programs with lot of logic or complex structure) and tasks related to managing the robot's system. This computer can then be connected to one or several controllers by an Ethernet network, or to one single controller by the controller's service port connection.

The main entry to the functionality of Robot Studio Online is a robot view explorer. From this you select which robot to work with, in cases where several robots are installed, and what parts of the system you want to work with.

Robot Studio Online contains:

- The *System Builder* for creating, installing and maintaining systems.
- A *configuration editor* for editing the system parameters of the running system.
- A *program editor* for online programming.
- An *event log* for monitoring and saving robot events.
- Tools for backing up and restoring systems.
- An administration tool for the User Authorization System.
- A *file manager* for transferring files between the PC and controllers.
- A *task window* for operating all kinds of tasks in the controller.
- Other tools for viewing and handling controller and system properties.

This thesis applies both software; the software tool and the robot studio, together in order to enable effective application. The software tool was used for creating the tool path data and adjusting robot configuration at some positions. Moreover, Robot Studio was used for modifying the tool path manually, simulating the robot configuration and conversing the tool path data from Cartesian Space Coordinate into Contonain.



CHAPTER 6.

CONCLUSION AND SUGGESTIONS

6.1 Conclusion

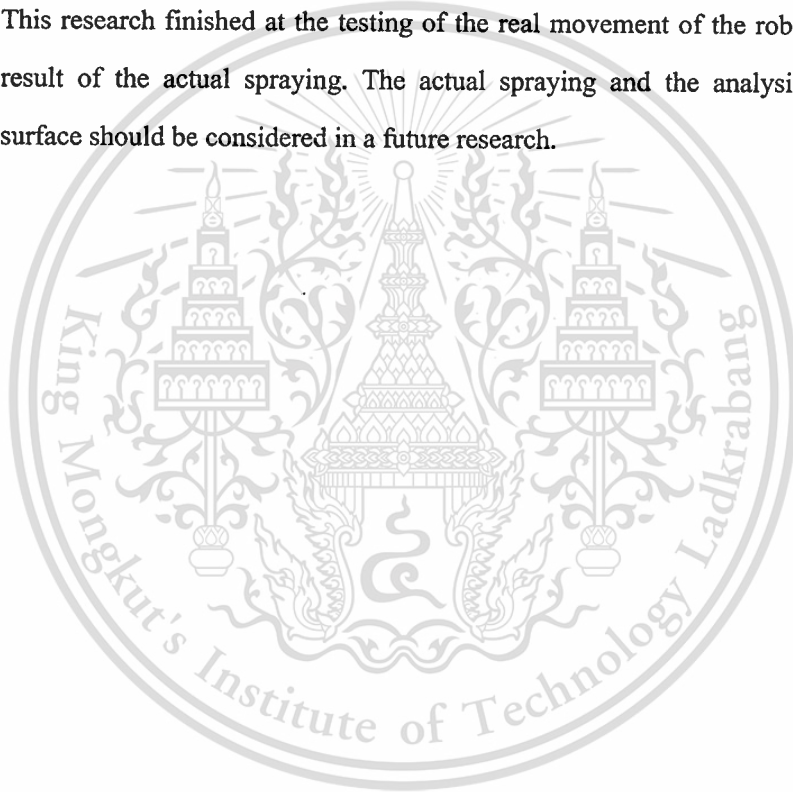
- 6.1.1 This research presented a procedure and algorithm is a part of the inner surface of transition piece plasma spray coating process which helps the robot to avoid collision and modify tool path automatically.
- 6.1.2 Automatic tool path modification contains two parts. The first part is Tool Path Adaptation to flee from Collision. In this part, there is an examination of collision between the transition piece and spraying tool. The program will simulate the movement of robot at every tool path data point and if a certain positions can cause collision, the robot will automatically adjust the tool path by itself to avoid the collision within a good spraying condition.
- 6.1.3 The second part is Tool Path Improving for Smoothly Robot Motion which will consider work piece curvature and regenerate tool path to get the tool path which has only necessary data points. It also helps in determining robot command to be more appropriate to the work as well.
- 6.1.4 All of this research work makes off line tool planning easier and more convenient which enable the user to spend less time and cost, and to perform more systematically than manual operation. Also, the adaptation technique efficiently controls the spray direction to be close to the initial path in order to control coating surface quality.
- 6.1.5 The procedure and algorithm of this research bases on fundamental concept which can be additionally applied with internal thermal spray coating on other models.

6.2 Suggestions

- 6.2.1 The tool path generated from the simulation is free from collision. However, in the real robot station, the path position may not be accurate as in the model. Therefore, robot

calibration is necessarily done for getting more accurate similarities of simulation model and real robot station.

- 6.2.2 Since the IRB 6650 robot has a large size and can cause high error in Absolute Accuracy. Therefore, there should be an addition of software and a system which can help calibrating the spraying gun, especially automatic plasma spraying gun because the gun is long and has a bending structure.
- 6.2.3 This research finished at the testing of the real movement of the robot, excluding the result of the actual spraying. The actual spraying and the analysis of the coating surface should be considered in a future research.



REFERENCES

- [1] Okada, K. , Inaba, M. and Inoue, H. “Real-time and Precise Self Collision Detection System for Humanoid Robots” **Robotics and Automation, ICRA Proc IEEE Int Conf**, April, 2005. Page 1060-1065
- [2] ColDet - Free 3D Collision Detection Library. <http://coldet.sourceforge.net/>.
- [3] S.H. Leigh and C.C. Berndt; “Evaluation of off-angle thermal spray” **Surface and Coatings Technology**, Volume 89, 1 March, 1997. Page 213-224
- [4] Anila Jahangiri and Richard Allor; “**Thermal Spray Control System**”
- [5] Kuu-Young Young and Chun-Yuh Huang “Collision-free path planning and modification based on task requirements” **Mechanism and Machine Theory**, Volume 32, January, 1997. Page 21-37
- [6] A. Candel and R. Gadow “Trajectory Generation and Coupled Numerical Simulation for Thermal Spraying Applications on Complex Geometries” **Journal of Thermal Spray Technology**, Published online : 21 July, 2009.
- [7] S. Ahmaniemi, P. Vuoristo, T. Mäntylä, J. Latokartano, Tampere/FIN, and I. Salonen, Linnavuori/ FIN “Optimisation of the robot controlled plasma spraying of thermal barrier coating for gas turbine transition duct” **ITSC Int Thermal Spray Conf**, 2002. Page 208-212
- [8] S. Deng, H. Li, H. Liao and C. Coddet “New Functions of Thermal Spray Toolkit A Software Developed for Off-line and Rapid Robot Programming” **Proc Int Thermal Spray Conf** (ASM International), 2006. Page 1437-1442
- [9] Liu, K. and et al., “Steward-platform-based inlet duct painting system” in **Proc IEEE Int Conf Rob Autom**, 1993. Page 106-113.
- [10] Yan Chen, Junyi Shao, Chuanqing Zhang, Chenglong Fu and Chen, K. “Redundant-robot-based painting system for variable cross-section S-shape pipe” **Reconfigurable Mechanisms and Robots, ASME/ IFToMM Int Conf**, June, 2009. Page 743–749
- [11] Pichler, A., Vincze, M., Andersen, H., Madsen, O. and Hausler, K. “A Method for Automatic Spray Painting of Unknown Parts” **Robotics and Automation, ICRA Proc IEEE Int Conf**, 2002. Page 444–449
- [12] Mahadevan Balasubramaniam, Stephen Ho, Sanjay Sarma and Yoshitaka Adachi “Generation of collision-free 5-axis tool paths using a haptic surface” **Computer-Aided Design**, Volume 34, Issue 4, 1 April,2002. Page 267-279

BIOGRAPHY

- Name:** Mr. Nattapon Aroonchote
- Date of Birth:** November 25, 1985
- Place of Birth:** Bangkok, Thailand
- Education:**
- | | |
|-----------|--|
| 2004-2008 | B. Eng. in Mechatronics Engineering , Department of Control Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang (KMITL) |
| 2008-2011 | M. Eng. in Automotive Engineering (International program), International College, King Mongkut's Institute of Technology Ladkrabang (KMITL) |
- Honor and Scholarships:**
- | | |
|-----------|---|
| 2008-2010 | Full scholarship for study in the master degree from National Science and Technology Development Agency (NSTDA) |
|-----------|---|
- Publications:**
1. N. Aroonchote, N. Naksuk, N. Depaiwa, and H. Yamaura. "Tool Path Planning Technique for Robot Plasma Spray Coating on Duct Component" **Proceedings of the IASTED International Conference Robotics (Robo 2010)**, Phuket, Thailand November 24 - 26, 2010. pp 69-73