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TITLE:

Operation of the Collaborative Composite Manufacturing (CCM) System

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KEYWORDS:

collaborative composite manufacturing (CCM) system, parallel robot, optical coordinate measuring machine (CMM), on-line pose correction algorithm, constraints, singularity

SUMMARY:

A collaborative composite manufacturing system is developed for robotic lay-up of composite laminates using the prepreg tape. The proposed system allows the production of composite laminates with high levels of geometrical complexity. The issues in the path planning, coordination of the robots and control are addressed in the proposed method.

ABSTRACT:

The automated tape placement and the automated fiber placement (AFP) machines provide a safer working environment and reduce the labor intensity of workers than the traditional manual fiber placement does. Thus, the production accuracy, repeatability and efficiency of composite manufacturing are significantly improved. However, the current AFP systems can only produce the composite components with large open surface or simple revolution parts, which cannot meet the growing interest in small complex or closed structures from industry.

In this research, by employing a 1-degree of freedom (DoF) rotational stage, a 6-RSS parallel robot, and a 6-DoF serial robot, the dexterity of the AFP system can be significantly improved for manufacturing complex composite parts. The rotational stage mounted on the parallel robot is utilized to hold the mandrel and the serial robot carries the placement head to mimic two human hands that have enough dexterity to lay the fiber to the mandrel with complex contour.

Although the CCM system increases the flexibility of composite manufacturing, it is quite time-consuming or even impossible to generate the feasible off-line path, which ensures uniform lay-up of subsequent fibers considering the constraints like singularities, collisions between the fiber

placement head and mandrel, smooth fiber direction change and keeping the fiber placement head along the norm of the part's surface, etc. Moreover, due to the existing positioning error of the robots, the on-line path correction is needed. Therefore, the on-line pose correction algorithm is proposed to correct the paths of both parallel and serial robots, and to keep the relative path between the two robots unchanged through the visual feedback when the constraint or singularity problems in the off-line path planning occur. The experimental results demonstrate the designed CCM system can fulfill the movement needed for manufacturing a composite structure with *Y*-shape.

INTRODUCTION:

Recently, the increasing need for high performance composite structures in various industries has greatly driven the development of the composite manufacturing technologies[1,2]. The traditional manual production cannot meet the high efficiency, accuracy and quality requirement of emerging industry. This aspect has encouraged the development of new production technologies such as AFP systems. The AFP technology automates the production of composite material structures using prepregs, which are present in the form of strips composed of impregnated fiber tapes (glass, carbon, etc.) of semi-polymerized resin. In the AFP system, a deposition head with the ability of heating and compacting the resin prepregs is mounted on a fiber placement machine or an industrial robot. The fiber placement machine or robot carrying the deposition head lays up the prepregs traversing the surface of the tooling mandrels. In the process of manufacturing, the tooling mandrel is used as a mold to be wound around by the prepregs to form a certain structure of composite part. The mandrel will be removed after the part is cured. The current AFP systems can significantly improve the efficiency and quality of the production of composite materials[3-5]. However, they are limited to the production of the open surfaces presenting a flat or contoured surface, or simple revolution parts such as cylinders or cones due to the insufficient DoF of the system and the difficulties in generating trajectories. Especially, the aerospace industry and the production industries of sports equipment are now interested in this technique for the production of structures with more complex geometries, like "Y" tubes or the structures forming closed-loops such as bicycle frames.

To be able to manufacture the structures with complex geometries, the flexibility of the AFP system should be improved. For example, an 8 DoF AFP system has been proposed[6] by adding a linear track to a 6 DoF industrial robot and a rotational stage to the mandrel holding platform. However, the system is still not suitable for manufacturing the above-mentioned parts with complex geometries. The collaborative robotic system consisting of two robots is a promising solution to increase the dexterity by employing one robot to hold the fiber placement head at the end-effector and another robot to hold the mandrel. The two-serial-robot collaborative system may not solve the fiber placement problem, since the serial robots tend to deform and lose the accuracy due to its cantilever structure, considering the weight of the mandrel and the compaction force[7]. Compared with the serial robots, 6 DoF parallel robots, which have been utilized in the flight simulator and medical tools, enjoy better stiffness and accuracy[8]. Therefore, a parallel-serial collaborative robot system, in additional to a rotational stage mounted on the platform of the parallel robot, is built for handling the complex structures manufacturing in this paper.

However, the built collaborative robotic system yields difficulties in designing the controller for each robot to meet the high accuracy requirement of fiber placement. The accurate position measurement of the end-effector could be achieved by using laser tracking system, which is commonly used to guide the industrial robot in various aerospace drilling applications[9,10]. Although the laser tracking system can provide high accurate position measurement, the main drawbacks lie in the cost of the system and the occlusion issue. The laser tracking system is expensive, e.g., a commercial laser tracker and its accessories cost up to US$90,000, and the laser beam is easily occluded during the movement of the robots. Another promising solution is the vision measurement system, which can provide 6D pose measurement of the end-effector with a considerable accuracy at a low cost. The pose is referred to as the combination of the 3D position and 3D orientation of the end-effector with respect to the base frame of the robot. The optical CMM (see **Table of Materials**) is a dual camera-based visual sensor. By observing several reflector targets attached on the end-effectors of the two robots, the relative poses between the robots can be measured in real time. The optical CMM has been successfully applied to the robotic calibration[11] and dynamic path tracking[12] and thus is introduced to provide the feedback measurement to the closed-loop control systems of the proposed CCM system in this study.

The quality of the end composite product is largely dependent on how the original fiber path is generated for the AFP[13,14]. The path generation process is normally performed by using off-line programming software. The generated path consists of a series of tag points on the mandrel, which indicate the pose of the fiber placement head. Unlike other trajectory planning applications such as paint deposition, polishing or machining, where different types of coverage paths are possible, the choice is limited in the case of AFP, since the fiber is continuous and it is not possible to perform abrupt changes in direction (sharp corners) without damaging it and the placement head should be kept in the norm of the surface of the parts. The first development of trajectory generation technique for AFP has been concentrated on manufacturing large flat panels[5] before moving towards the manufacturing the objects of 3D shapes such as open curved surfaces or cones[5,14]. But, no practical methodology has been developed for generating off-line path for the parts with complex geometries such as Y-shape or the other shapes. Therefore, an effective path planning algorithm for the parts with complex-contoured surfaces is designed to ensure uniform lay-up of subsequent fibers without gaps or overlaps in our previous research[15]. Considering the practicality and the effectiveness of the path generating algorithm, only the 6-DoF serial robot with the placement head and 1-DoF rotational stage as the mandrel holder are considered as the target system to find the optimum trajectory planning in joint space with minimum time criteria. It could be too complicated and time-consuming to generate the off-line trajectory for the whole 13 DoF CCM system due to the heavy kinematics calculation and the consideration of various constraints like singularities, collisions, smooth direction changing and keeping the placement head in the norm of the parts surface, etc.

The proposed off-line trajectory planning can generate the servo reference for the 6 DoF serial robot and the rotational stage respectively with exact timing. Even with this off-line trajectory planning, it could be impossible to generate a feasible path under all the constraints for certain geometry parts. Moreover, the positioning errors of the robots may cause the robots to collide with the mandrel or another device in the working environment. The on-line path modification is implemented based on the visual feedback from the optical CMM. Therefore the on-line pose correction algorithm is proposed to correct the path of the parallel robot and to tune a corresponding offset on the path of the serial robot simultaneously through the visual feedback. When the collision and other constraints are detected, the relative pose between the two robots is also kept unchanged while following the off-line generated path. Through the correction of the on-line path, the CCM system can avoid these points smoothly without any termination. Due to the flexibility of the parallel robot, the 6D correction offsets can be generated with respect to different constraints. This manuscript presents a detailed operation procedure of the CCM system using on-line pose correction algorithm.

PROTOCOL:

1. Frame Definitions of the CCM system

NOTE: The optical CMM is a dual camera sensor, which can track the object with a rigid set of reflectors as the targets in real time. The placement principle of these targets is that the targets are stuck at the asymmetric locations with certain distance among them. The targets need to be fixed on the robots or the placement head and remain in the field of view (FOV) of the optical CMM. At least four targets should be observed for each defined frame by the optical CMM all the time. The base frame of the parallel robot, the end-effector frame of the parallel robot, and the tool frame of the serial robot are denoted as F_b, F_t^P, and F_t^S, respectively. The definitions of those frames are shown in **Figure 1**. Because the base frames of the parallel robot and the serial robot are fixed, the transformation matrix between the two base frames can be derived by calibration.

[Place **Figure 1** here]

1.1. Definition of the base frame of the parallel robot

1.1.1. Load the frame definition file through the software of the optical CMM (see the **Table of Materials**).

1.1.2. Click **Positioning** > **Detect Targets**. Select the targets that are attached on the motors of the parallel robot. Click **Accept** to take those targets as the positioning reference of the whole system.

1.1.3. In the **Entities** list, click **Base Frame** and select **Make this Reference Frame the Origin**.

NOTE: The purpose of Step 1.1 is to take F_b as the reference frame of the whole system. The frame definition file can be obtained at the following link: <https://users.encs.concordia.ca/~wfxie/Jove_program/P3.csf>.

1.2. Definition of the tracking model of the end-effector platform frame

1.2.1. Select **Tracking Models** in the navigation area. Click **Detect Model**, and then select the targets fixed on the end-effector platform of the parallel robot. Click **Accept**.

1.2.2. Click the generated detection model. Select **Up_Frame** in the drop-down list of the **Origin Offset**. Then click **Apply**.

NOTE: This step is to set up the fixed relationships between the end-effector platform frame F_t^P and the targets attached on the end-effector platform.

1.2.3. Click **File-Export-Tracking model**, and enter a file name to save the tracking model.

1.3. Definition of the tracking model of the tool frame

1.3.1. Select **Tracking Models**. Click **Detect Model**, then select the targets fixed on the tool frame of the serial robot. Click **Accept**.

1.3.2. Click the generated detection model. Select **SerToolFrame** in the drop-down list of the **Origin offset**. Click **Apply** and save the defined tracking model.

2. System Preparation

NOTE: The control system layout of the CCM system is shown in **Figure 2**.

[Place **Figure 2** here]

2.1. Preparation of the rotational stage

2.1.1. Load the integrated control interface programed by event-driven programming language on computer A.

NOTE: The control interface is shown in **Figure 3**. The interface program can be obtained at the following link: <https://users.encs.concordia.ca/~wfxie/Jove_program/pcdk-ctrack.rar>.

[Place **Figure 3** here]

2.1.2. Click **Connect** to connect the controller of the rotational stage. Click **Enable** to connect the motor of rotational stage. Then click **Home** to move the rotational stage to the home position.

2.2. Preparation of the serial robot

2.2.1. Power on the controller of the serial robot (see the **Table of Materials**).

2.2.2. Click **Connect** on the integrated control interface to connect the robot server.

2.3. Preparation of the Optical CMM

2.3.1. Power on the controller of the optical CMM and wait until the screen of the controller shows **Ready**.

2.3.2. Click **Connect** on the integrated control interface to connect the optical CMM via Application Programming Interface (API).

2.3.3. Import the models built in section 1, which includes the Base model, the Upper platform model and the End-effector model of the serial robot.

2.3.4. Click **Add Sequence**. Add the relative sequence between the models if it is necessary. Then click **Start Tracking** to track the pose of the models.

2.4. Preparation of the Parallel robot

2.4.1. Power on the controller of the parallel robot.

2.4.2. Load the **SerialPort_Receive** program and select **Normal** mode.

NOTE: The **SerialPort_Receive** program cannot control the parallel robot directly. It is used to receive the remote data from computer A via serial communication port. The **SerialPort_Receive** program can be obtained at the following link: <https://users.encs.concordia.ca/~wfxie/Jove_program/SerialPort_Receive.mdl>.

2.4.3. Load the **ParaRemoteControl** program and select **External** mode. Then click **Incremental Build** to connect to target.

NOTE: The **ParaRemoteControl** program is used to receive the desired pose from **SerialPort_Receive** program and control the parallel robot. The **ParaRemoteControl** program can be obtained at the following link: <https://users.encs.concordia.ca/~wfxie/Jove_program/ParaRemoteControl.mdl>.

2.4.4. Click **Start Simulation** of the two programs to initialize the controller of the parallel robot.

3. Generating the off-line path

3.1. Load the path planning interface through the numerical computing software (see the **Table of Materials**).

NOTE: The interface is shown in **Figure 4**. The path planning interface is the off-line software to generate the path for the system and can be obtained at the following link: <https://users.encs.concordia.ca/~wfxie/Jove_program/AFP_PathPlanning_Pcode.zip>.

[Place **Figure 4** here]

3.2. Click **Import STL** and choose the part file. Then click **Segmentation**.

NOTE: The part is divided into separated regions (cylinders and junctions of Y-shape part). The different regions are displayed in different colors.

3.3. Click **Add Work Region** and select the region on the extraction of cylinders.

3.4. Adjust the slider to 100% and click **Extract Cylinders**.

3.5. Click **Add Work Region** to select the starting branch of the path.

3.6. Click **Generate Path**. Choose the third option: **Constant Placement Angle (CPA)** in the pop-up dialog window.

3.7. Choose the desired placement angle 90° in the pop-up dialogue window. Then choose the red dot.

3.8. To display the generated path, click **Select a Path** drop-down menu. Then, select the path.

3.9. To save this path, click **File** > **Save** and enter a file name.

4. Individual decomposition of the trajectory for the serial robot and rotational stage

4.1. Run the **Methode_Jacobian** function in the numerical computing software (see **Table of Materials**).

NOTE: **Methode_Jacobian** function is used to decompose the generated path in Step 3 into two individual trajectories for the serial robot and the rotational stage.

4.2. Select the desired path file (generated by path planning interface) and click **open**.

4.3. Enter the desired path number.

4.4. The first point of the trajectory is then calculated. Choose the desired configuration for the manipulator to reach this pose.

NOTE: When Step 4.4 is completed, a graph showing the evolution of joint values is displayed. A file containing the trajectory for the serial robot and the rotational stage is generated.

5. Running the off-line path without the path modification algorithm

5.1. Press **Select** on the teach pendant and choose the name of the imported file. Press **Enter** to load the path file.

5.2. Turn the switch of the robot controller to **Auto** mode. Turn the teach pendant ON/OFF switch to **Off**.

5.3. Press **Cycle Start** of the controller of the serial robot to run the path.

5.4. Click **Cooperative Move** located at the **Cooperative Control** panel.

NOTE: The system will execute the offline path without the on-line path modification algorithm. If the joint reaches to the singularity or constraint condition, the system will stop.

6. Running the off-line path with the path modification algorithm

6.1. Repeat steps 5.1–5.3. Then click **DPM Connect** located at the **Cooperative Control** panel in **Figure 3** to add the on-line path modification ability for the system.

6.2. Click **Cooperative Move** located at the **Cooperative Control** panel.

NOTE: The system will execute the offline path with the on-line path modification algorithm. During the execution, the singularities and joints' constraints are monitored through the encoder measurement of the serial robot. The system can smoothly pass the singularity or constraint limitation points without termination.

REPRESENTATIVE RESULTS:

The experiment aims at demonstrating the process of realizing the motion of laying up the fiber on the Y-shape mandrel of the proposed CCM system. The process is carried out in three steps: path generation; trajectory decomposition; and singularity and constraint avoidance.

Path generation

Normally, the standard orientation is used in industry to define the different plies of the laminate. In this paper, the orientation definition should be adapted to the Y-shape body. By taking the central axis of the mandrel as a reference, namely 0°, three different orientations of the ply, 0°, 45°, and 90° are studied for the practical composite industrial application. The path generation for 90° ply orientation is shown as an example. The 90° ply is obtained as a helix curve course, whose pitch is the width of composite tapes. Therefore, the actual angle between the course and the reference is close to 90°. The generated 90° ply can cover two branches without any interruption, and the overlaps and gaps between tapes can be minimized. As shown in **Figure 5**, the three branches of the part are labeled as *A*, *B*, and *C*. The first trajectory is generated to cover branches *A* and *B* but leave branch *C* uncovered. To cover branch *C*, branches *B* and *C* are considered to generate the second trajectory. Lastly, another 90° ply is generated to cover branches *A* and *C*. After following the above procedures, two layers are generated for each branch.

[Place **Figure 5** here]

Trajectory decomposition

Trajectory decomposition defines the trajectory of each robot independently to avoid collision with each other. The pressure of fiber placement head's compression roller must be normal to the surface of mandrel and the axis of the compression roller should always be kept perpendicular to the trajectory path during the manufacturing processes. The mandrel is mounted on the rotational stage which is fixed on the upper platform of parallel robot. The kinematic relationship between the end-effectors of two robots is pre-planned and known.

Figure 6 illustrates the decomposing process of continuously wrapping two branches of the Y-shape mandrel with constant 90° placement angle. It can be decomposed to the trajectory of serial robot and rotary movement of rotational stage. The decomposed trajectories can guarantee the roller would be normal to the mandrel surface. As mentioned above, after finishing wrapping from branch *A* to branch *B*, another layer is wrapped from branch *B* to branch *C*. Then, a new layer is started from branch *A* to branch *C* and the wrapping cycle keeps iterative.

[Place **Figure 6** here]

Singularity and constraints avoidance

The trajectory generated off-line for the CCM system inevitably consists of singular points and constraints in some cases. For instance, the wrist singularity of the serial robot occurs when the axes of Joint 4 and Joint 6 are coincident due to the fact that the rotational angle of Joint 5, θ_5, is equal to or close to 0°. The developed avoidance algorithm can simultaneously move the 6-RSS platform and the serial robot in order to lay up the fiber following the generated off-line trajectories. In the built-in controller of the serial robot, a safe threshold angle for Joint 5 is 3.5°, which means the robot will automatically stop when $\theta_5 \leq 3.5$. Considering the reachability of the serial robot and the sensitiveness of the singularity detection, 4.0° is selected as the optimal threshold ($\Delta\theta_{5min}$) for this kind of singularity avoidance through a large amount of experiment. The trigger condition for the singularity avoidance mechanism is $|\theta_5(k)| < \Delta\theta_{5min}$. In the on-line pose correction algorithm shown in **Figure 7**, the encoder of Joint 5 of the serial robot is monitored. If Joint 5 meets the singularity trigger condition, the integrated control interface software will generate the offset ΔP_p^o for the parallel robot and add the correction to the off-line path of the serial robot accordingly. When Joint 5 passes the pre-defined threshold, the parallel robot moves back to its initial pose and the on-line path correction of the serial robot stops.

In the experiment, an off-line planning path is generated for manufacturing the Y-shape composite part, in which joint wrist singularity occurs. The experiment results show that the proposed method can create the pose correction for the parallel robot and adjust the off-line path of the serial robot based on the optical CMM feedback. In this way, the system can smoothly pass the singularity and lay up the fiber along the path without termination as shown in **Figure 8**] Therefore the proposed CCM system can accomplish the manufacturing process of the structure with Y-Shape successfully.

[Place **Figure 7** here]

[Place **Figure 8** here]

FIGURE AND TABLE LEGENDS:

Figure 1. Collaborative Composite Manufacturing (CCM) System Setup. The hardware of the CCM system consists of a 6-RSS parallel robot, a 1-DoF rotational stage, a 6-DoF serial robot, a placement head, and the optical CMM. The mandrel is clamped on the rotational stage, and the rotational stage is mounted on the parallel robot.

Figure 2. System Layout. Two computers (A & B) are used for controlling the CCM system. The communication between them is via RS232. Computer A controls the rotational state, photogrammetry senor and serial robot. Computer B controls the parallel robot, motors and valves etc.

Figure 3. Control Interface. The control software programmed by event-driven programming language. The interface is composed of 6 sections: serial robot, parallel robot, rotational stage, path import, optical CMM and cooperative control.

Figure 4. Path Planning Interface. The path planning software is composed of 3 sections: Visual Area, Command Area and Information Box. The “Viewing Area” section allows the 3D display of the parts to be processed. The “Command Area” section is to perform the main actions for generating the off-line path. The “Information Box” section displays the information about the status of the program.

Figure 5. The First Generated Trajectory of 90° Ply. The first path is generated to cover branches *A* and *B* with a continuous course while minimizing the gaps and overlaps. Similarly, the second path is generated to cover branches *B* and *C* and the third one is to cover branches *A* and *C* to obtain the uniform coverage of mandrel. The trajectory is iteratively generated by following the same procedure.

Figure 6. The Decomposition for Y-Shape Trajectory. The generated trajectory is decomposed to the trajectories of serial robot and rotary movement of rotational stage. The decomposing process aims at continuously wrapping two branches of the *Y*-shape mandrel with constant 90° placement angle. Angle α is the orientation of serial robot’s end-effector. Vector e_2 is the normal unit vector that guarantees the roller would be normal to the mold surface. In the helix part of the trajectory for the serial robot, the pitch is equal to the width of the tapes. The roller offsets are along the direction of the vector e_3.

Figure 7. Flow Chart of On-line pose correction algorithm. Flow chart outlining the procedures for running on-line pose correction algorithm. It consists of the procedure of wrist singularity avoidance and the procedure of joint constraints avoidance.

Figure 8. Trajectory Comparison with and without Wrist Singularity Avoidance, a) the 3D workspace course, b) the angular trajectory of Joint 5, and c) The orientational trajectory of the parallel robot. (**a**) The actual workspace course of the tape with and without wrist singularity avoidance are given. The black line shows that when Joint 5 reaches the range -3.5° ≤ J5 ≤ 3.5°, the system stops due to the safe threshold angle setting in the robot controller. The blue dash line demonstrates the robot can smoothly pass the joint limits and complete the rest course by using the avoidance algorithm to generate the correction paths for both the parallel and serial robots. (**b**) The trajectory of Joint 5 terminates around 24 s without the proposed avoidance algorithm when the serial robot moves near its singularity point (i.e., 4.0°). (**c**) The actual trajectories of the parallel robot, including the Y-direction Euler angle of the end-effector pose, are given. The blue line shows the original path of the robot without any on-line correction, and the red line illustrates that the correction path is added to the robot when Joint 5 is close to 4.0°.

DISCUSSION:

The experimental results show the manufacturing process of 90° ply placement angles of the designed CCM system. The methodologies proposed in this paper can be used to lay up the fiber with 0° and 45° ply placement angles on the mandrel with Y-Shape and other shapes. While the built-in controller of the serial robot is able to provide the singularity avoidance feature[17], only linear movement of the end-effector is supported. When the end-effector executes the task of the circle movement, the feature does not work and hence the generated desired off-line path cannot be ensured. Moreover, the joint constraint problem cannot be solved through the built-in controller features. Therefore in this paper, an on-line path correction method is proposed to overcome the mentioned drawbacks by generating the optimal correction pose for the serial and parallel robots, and to keep the relative path between the two robots to follow the off-line path based on the optical CMM feedback. The triggering conditions for joint limits and singularities indicate the moment when the controller sends the movement command signal to drive the parallel robot and correspondingly to modify the serial robot path. Triggered by the constraint and singularity situations of the serial robot, the optimal path correction of the parallel robot is generated with the objective of minimum parallel robot movement. Compared with the current AFP machines, the CCM system has the potential to manufacture small composite components of complex geometry.

The critical steps within the protocol are the generation of pose correction and input to both of the robots. The pose correction for the trajectory of the serial robot is carried out by Dynamic Path Modification (DPM) provided by the serial robot. The response time is relatively long, which results in the error of the relative poses of the two tool frames.

Our future plans include developing an advanced model-based controller for improving the path tracking accuracy for the CCM system, designing a filter to remove the noise in the optical CMM measurement, and using the developed CCM system to manufacture the actual composite structures.

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DISCLOSURES:

The authors have nothing to disclose.

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Figure 1

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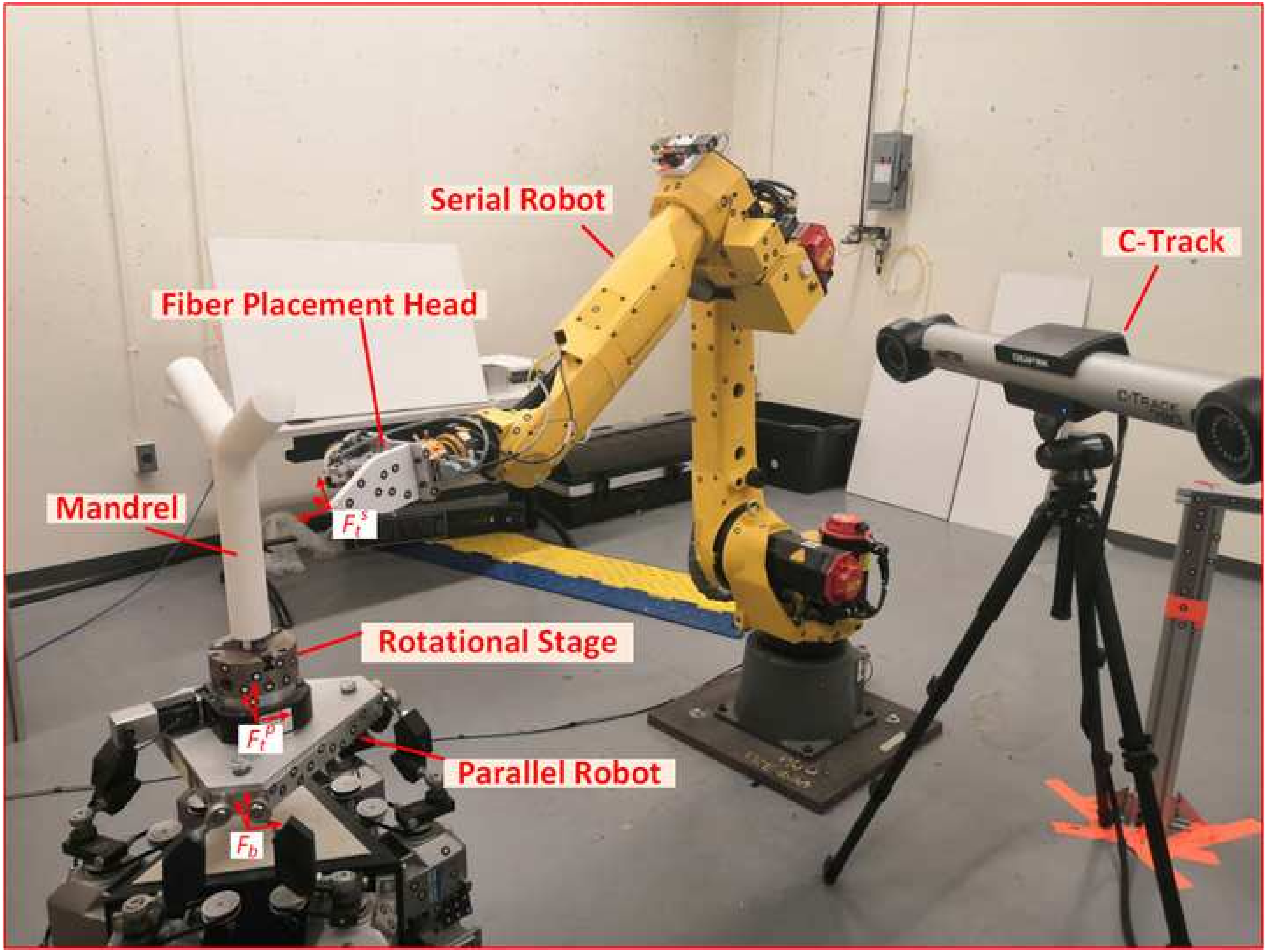


Figure 2

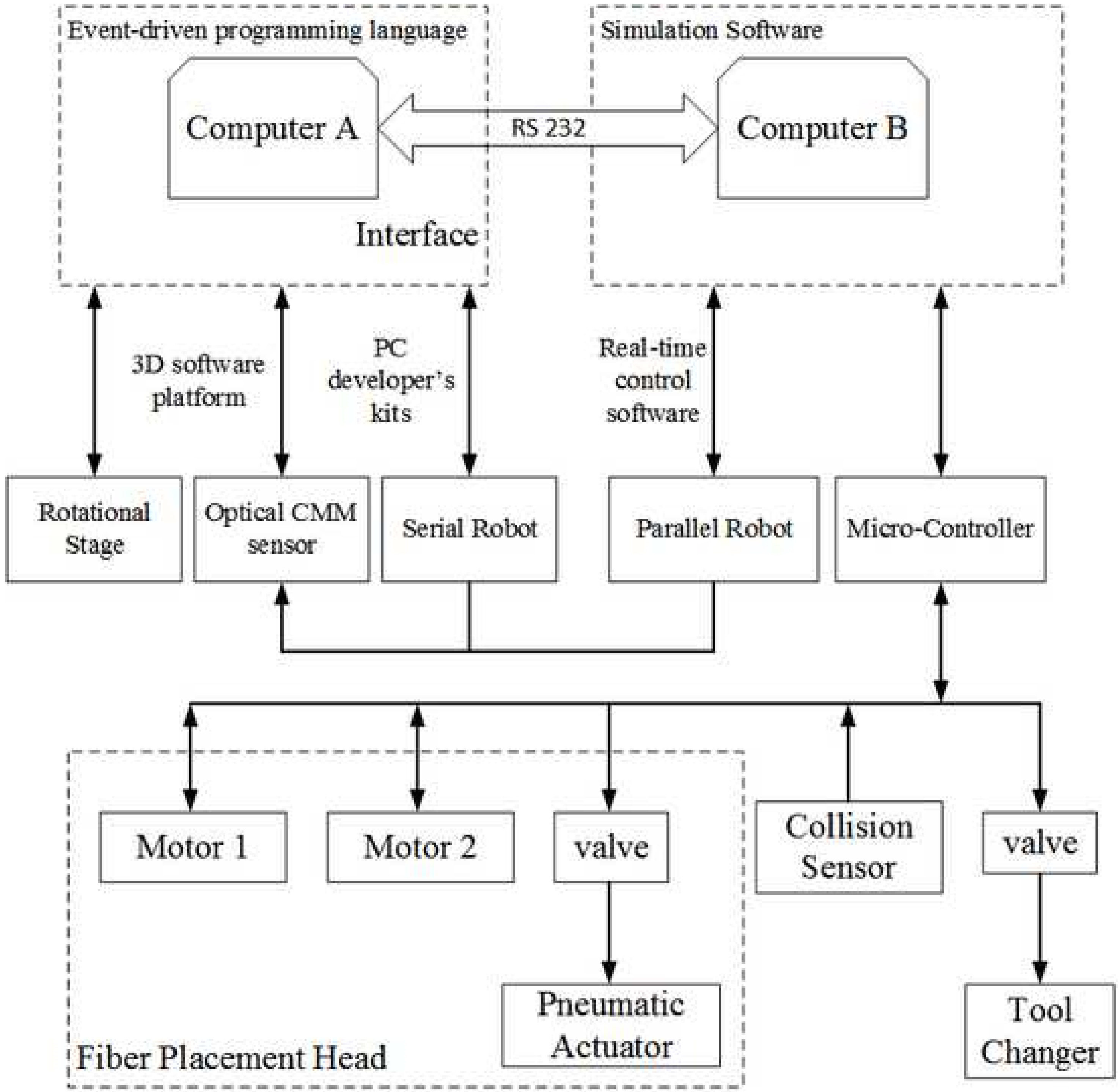

Event-driven programming language
Computer A
RS 232
Simulation Software
Computer B
Interface
3D software platform
PC developer's kits
Real-time control software
Rotational Stage
Optical CMM sensor
Serial Robot
Parallel Robot
Micro-Controller
Motor 1
Motor 2
valve
Collision Sensor
valve
Pneumatic Actuator
Tool Changer
Fiber Placement Head

Figure 3

Click here to access/download;Figure;Figure 3. Control Interface.tif

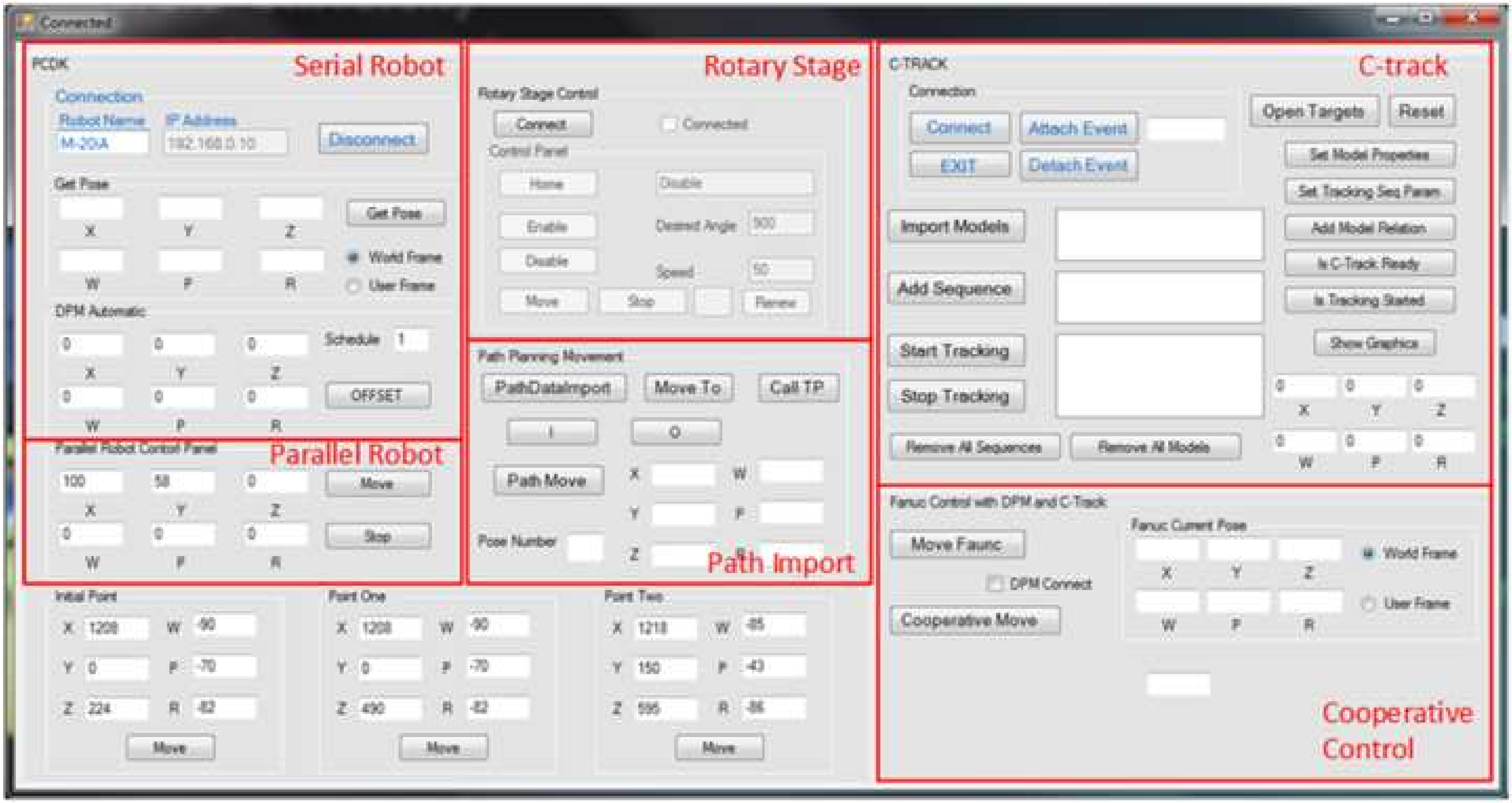


Figure 4 Click here to access/download;Figure;Figure 4. Path Planning Interface.tif

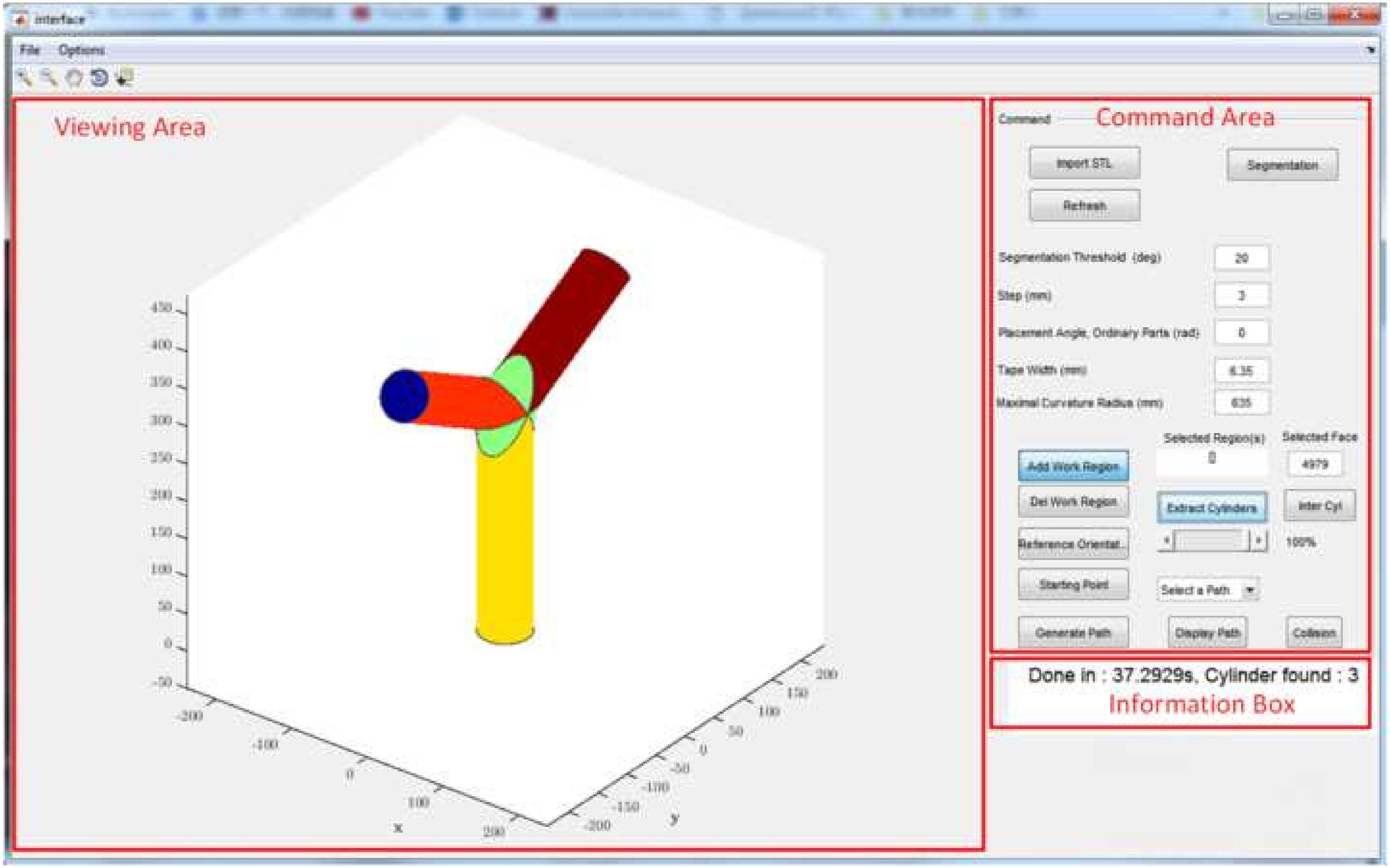


Figure 5

Click here to access/download;Figure;Figure 5.The First Generated.tif

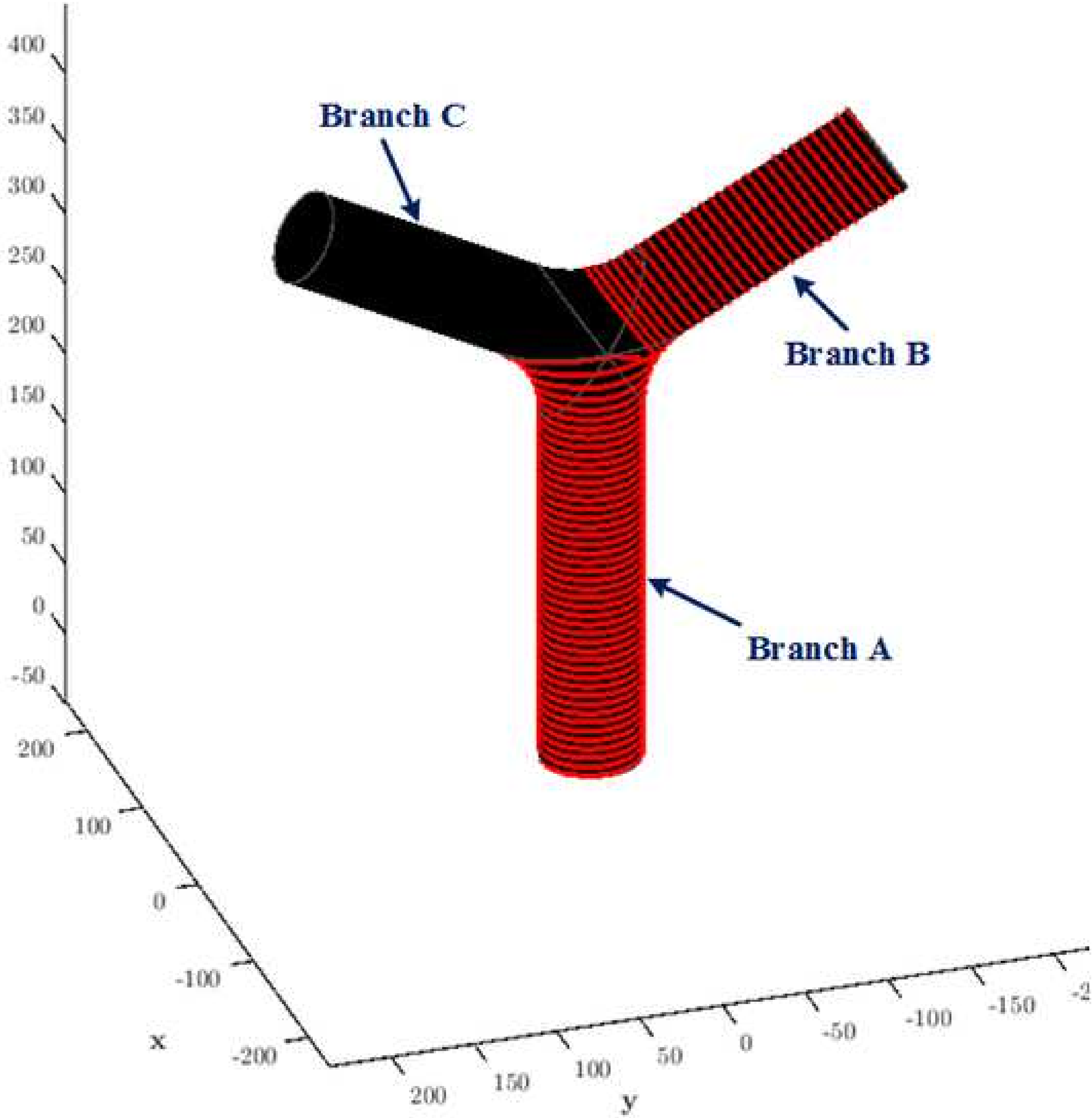


Figure 6

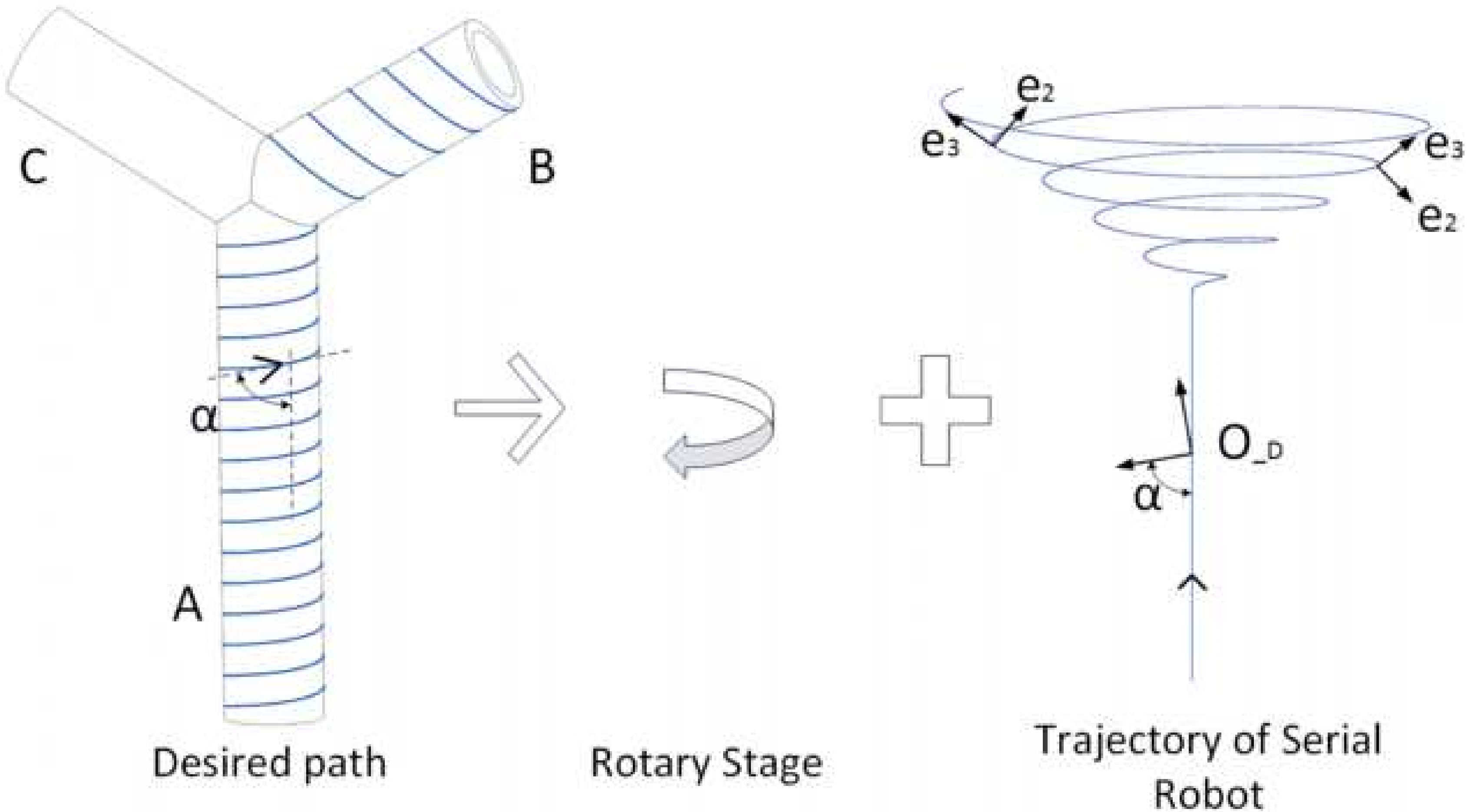

C
B
A
α
Desired path
Rotary Stage
e2
e3
e3
e2
O_D
α
Trajectory of Serial Robot

Figure 7

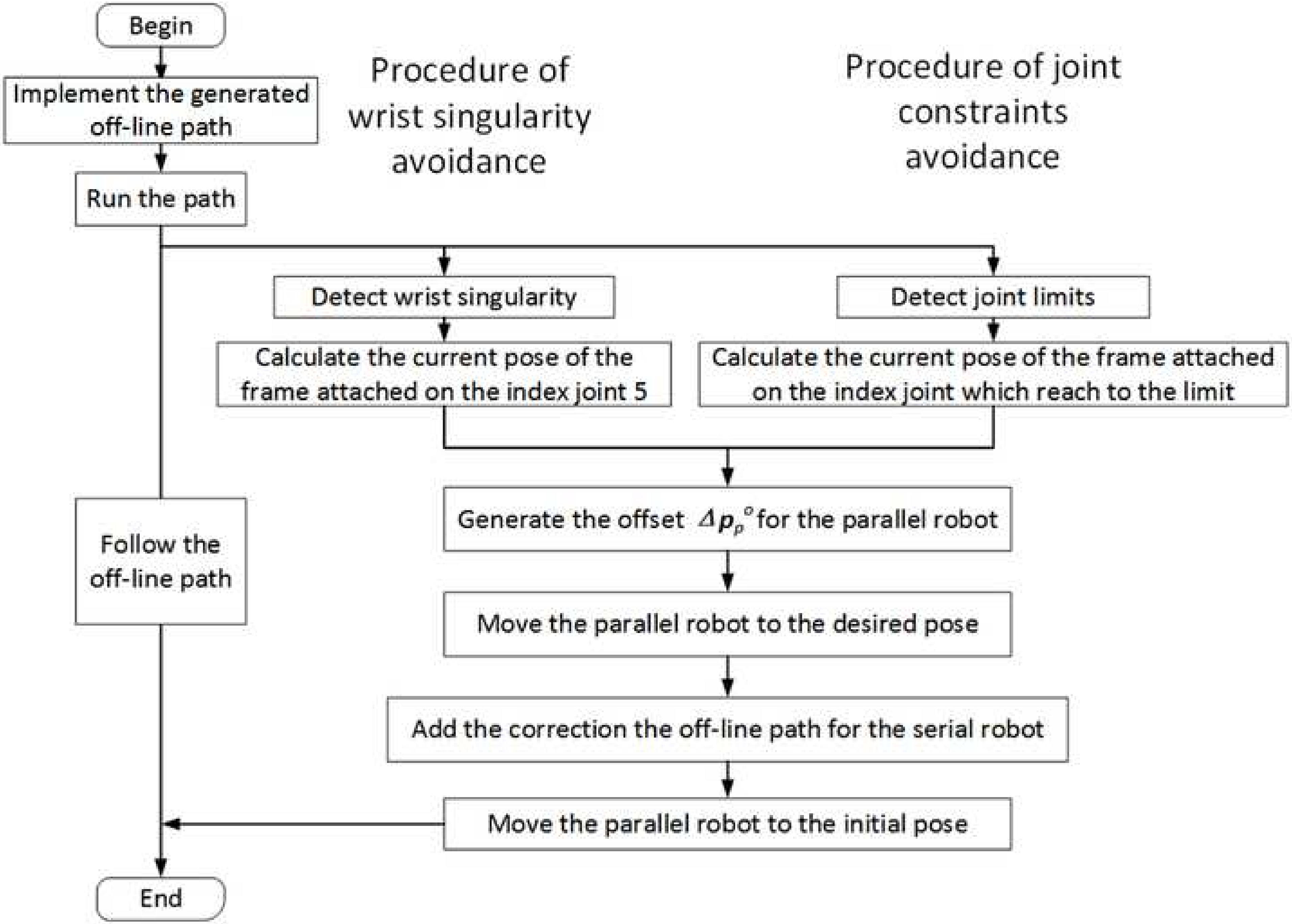
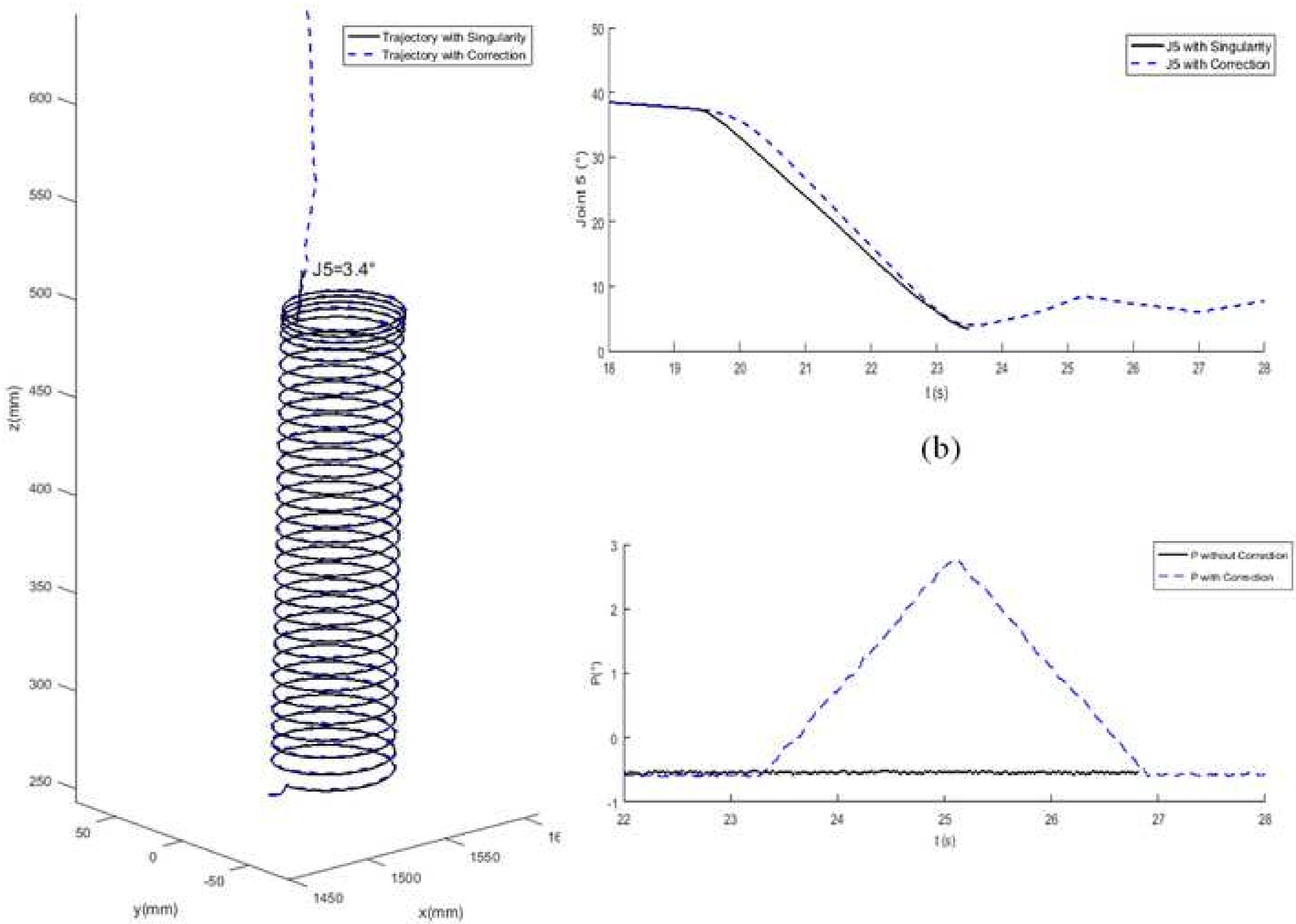

Begin
Implement the generated off-line path
Run the path
Procedure of wrist singularity avoidance
Procedure of joint constraints avoidance
Detect wrist singularity
Detect joint limits
Calculate the current pose of the frame attached on the index joint 5
Calculate the current pose of the frame attached on the index joint which reach to the limit
Follow the off-line path
Generate the offset Δp_p^o for the parallel robot
Move the parallel robot to the desired pose
Add the correction the off-line path for the serial robot
Move the parallel robot to the initial pose
End

Figure 8

Click here to access/download;Figure;Figure 8.Trajectory Comparison with and without.tif



(a)

(b)

(c)

Name of Material/ Equipment	Company	Catalog Number
AeroBasic	Aerotech	
Collaborative Composite Manufacturing (CCM) System	Concordia University	
C-track	Creaform Inc.	
Fanuc M-20iA	Fanuc Inc.	
Matlab	MathWorks	
Quanser	Quanser Inc.	
VB	Microsoft	
Vxelements	Creaform Inc.	

Comments/Description

Motion control software

A CCM system is proposed to manufacture more complex composite components which pose high demand for trajectory planning than those by the current AFP system. The system consists of a 6 degree-of-freedom (DOF) serial robot holding the fiber placement head, a 6-DOF revolute-spherical-spherical (RSS) parallel robot on which a 1-DOF mandrel holder is installed and an eye-to-hand optical CMM sensor, i.e. C-track, to detect the poses of both end-effectors of parallel robot and serial robot.

An eye-to-hand optical CMM sensor

Serial robot

A multi-paradigm numerical computing software

Providing the engineering lab equipments for teaching and research.

Visual Basic

Software for C-track

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Author(s):	Pengcheng Li, Xiaoming Zhang, Wenfang Xie, S.V. Hoa

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Authors' Responses to Editor

Dear Editor,
Thank you for your comments on our manuscript. In the following, we have addressed each comment.

Editorial comments:
1. Are the "SerialPort_Receive", "ParaRemoteControl", and "Methode_Jacobian" functions ones you have written, or are they available within the control/analysis software? If the former, please provide them (and any other programs you may have written for this protocol) as supplemental material or provide a link in the manuscript to where they can be obtained.

Response: Yes, the above-mentioned functions are developed by us. The link for the programs and functions written by us is provided as:
https://users.encs.concordia.ca/~wfxie/Jove_program/.
And in the manuscript, we also added the link to the program wherever it is needed for the readers to download. The modifications are shown as following:

> "1.1.1 Load the frame definition file through the software of the optical CMM (see the Table of Materials).
> …
> Note: The purpose of Step 1.1 is to take F_b as the reference frame of the whole system. The frame definition file can be obtained by clicking this link."
>
> "2.1.1 Load the integrated control interface programed by event-driven programming language on computer A.
> Note: The control interface is shown in [Figure 3]. The interface program can be obtained by clicking this link. "
>
> "2.4.2 Load "SerialPort_Receive" program and select ''Normal'' mode.
> Note: The "SerialPort_Receive" program cannot control the parallel robot directly. It is used to receive the remote data from computer A via serial communication port. The "SerialPort_Receive" program can be obtained by clicking this link.
> 2.4.5 Load ''ParaRemoteControl" program and select "External" mode. Then click "incremental build" to connect to target.
> Note: "ParaRemoteControl" program is used to receive the desired pose from "SerialPort_Receive" program and control the parallel robot. The "ParaRemoteControl" program can be obtained by clicking this link. "
>
> "3.1 Load the path planning interface through the numerical computing software (see the Table of Materials).
> Note: The interface is shown in [Figure 4]. The path planning interface is the off-line software to generate the path for the system and can be obtained by clicking this link. "

"4.1 Run the "Methode_Jacobian" function through the numerical computing software."

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"**SHORT ABSTRACT:**

A collaborative composite manufacturing system is developed for robotic lay-up of composite laminates using the prepreg tape. The proposed system allows the production of composite laminates with high levels of geometrical complexity. The issues in the path planning, coordination of the robots and control are addressed in the proposed method."

"**LONG ABSTRACT:**

The automated tape placement and the automated fiber placement (AFP) machines provide a safer working environment and reduce the labor intensity of workers than the traditional manual fiber placement does. Thus, the production accuracy, repeatability and efficiency of composite manufacturing are significantly improved. However, the current AFP systems can only produce the composite components with large open surface or simple revolution parts, which cannot meet the growing interest in small complex or closed structures from industry.

In this research, by employing a 1-DOF rotational stage, a 6-RSS parallel robot, and a 6-DOF serial robot, the dexterity of the AFP system can be significantly improved for manufacturing complex composite parts. The rotational stage mounted on the parallel robot is utilized to hold the mandrel and the serial robot carries the placement head to mimic two human hands which have enough dexterity to lay the fiber to the mandrel with complex contour. The system setup is shown in [Figure 1].

Although the CCM system increases the flexibility of composite manufacturing, it is quite time-consuming or even impossible to generate the feasible off-line path, which ensures uniform lay-up of subsequent fibers considering the constraints like singularities, collisions between the fiber placement head and mandrel, smooth fiber direction change and keeping the fiber placement head along the norm of the part's surface etc. Moreover, due to the existing positioning error of the robots, the on-line path correction is needed. Therefore, the on-line pose correction algorithm is proposed to correct the paths of both parallel and serial robots, and to keep the relative path between the two robots unchanged through the visual feedback when the constraint or singularity problems in the off-line path planning occur. The experiment results demonstrate the designed CCM system can fulfill the movement needed for manufacturing a composite structure with Y-shape.
"

3. Where possible, please write variables in the same font as the rest of the text (i.e., not in equation editor). If they are not, they will be formatted differently in the final version of the manuscript.

Response:

We modified all the variables written in equation editor to the text font.