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Optimization of Robot and Positioner Motions in Manufacturing of High-pressure Composite Vessels

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Abstract: The paper proposes a technique for optimal motions generation in redundant robotic tape winding systems for manufacturing of high-pressure composite vessels. It also presents two industrial case studies dealing with the motion generation for basic types of winding lamina, helical and circumferential. The developed technique transforms the original continuous problem into a discrete one where the desired time-optimal motions are presented as a shortest path on the task graph satisfying the problem-specific acceleration and velocity constraints imposed on the joint coordinates. It allows generating the optimal trajectories using enhanced dynamic programming algorithm that considers both of these constraints. Efficiency of the developed technique is confirmed by simulation studies.

Keywords: Redundant robotic system, Time-optimal motion, High-pressure composite vessel.

1. INTRODUCTION

High-pressure vessels are containers designed to hold gases or liquids under a pressure substantially higher than the ambient one. Common pressure vessels are made of steel. However, since rolled and forged parts are welded together during fabrication, some mechanical properties could be adversely affected. The latter requires increasing of the thickness to resist the high pressure. For this reason, such all-metal construction is usually very heavy, weighing approximately 1.4 kg/L. To save the weight, there are some other manufacturing techniques based on composite materials (see Fig. 1). In particular, the construction of metal liner with full composite overwrap (generally aluminium with a carbon fiber composite) and all-composite structure comprising a polymer liner with carbon fiber composite allows achieving the weight parameter from 0.3 to 0.5 kg/L (Legault, 2012, Boiler and Code, 1989, Hoa, 2017). For fabricating composite vessel, automated tape winding technique is usually used (Frketic et al., 2017). Relevant technological process can be implemented by using either specifically designed CNC machines or robotic systems. Existing CNC machines have no limitations on the component size, but they are expensive and require large work-floor areas. In contrast, the robotic systems are relatively cheap and flexible. However, they are usually kinematically redundant because of excessive number of actuated axes that are provided by a 6-dof robot, a 1-dof positioner and a 1-dof linear track. For this reason, optimal coordination of the manipulator motions with the positioner/track movements is an important issue in the robotic tape winding processes.

In literature, there are a number of works that deal with redundancy resolution. Relevant techniques are usually based on the pseudo inverse of the kinematic Jacobian (Flacco and De Luca, 2015). However, they can be hardly applied to the considered problem because they do not allow generating optimal trajectories satisfying real-life industrial requirements (Kazerounian and Nedungadi, 1988). Alternatively, there are also several techniques based on conversion of the original continuous problem to a discrete one. The simplest one is able to generate time-optimal trajectories for point-to-point motions and was applied to the spot-welding (Gueta et al., 2017, Gueta et al., 2011). A slightly different method was proposed in (Pashkevich et al., 2004) for the laser cutting and arc-welding applications where the motion amplitude for the actuated axes was minimized but the tool speed was assumed to be constant.

For the considered process, where the tool speed variations are allowed in certain degree, a discrete optimization based methodology was proposed in our previous work (Gao et al., 2017b, Gao et al., 2017a). It allows the user to convert the original problem to the combinatorial one taking into account particularities of the fiber placement technology and to generate time-optimal coordinated motions for the robot and positioner. However, the technique was applied to a planar benchmark example only, with a single redundant variable. In this work, an extension of the previous results is proposed allowing dealing with the optimal motion coordination for robotic systems for two basic types of winding paths (helical and circumferential, respectively) in the manufacturing of high-pressure composite vessels.

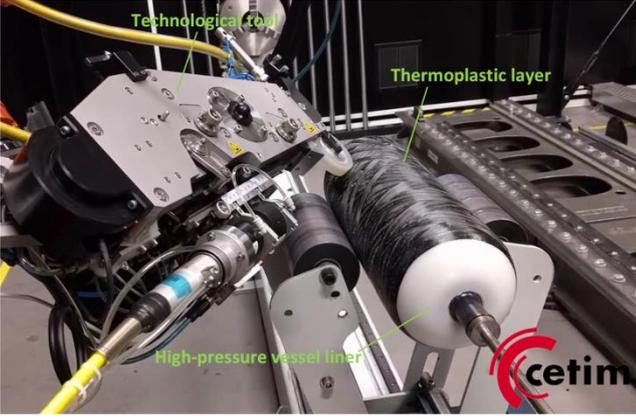


Fig. 1. Manufacturing of the high-pressure composite vessel with thermoplastic tape covering.

2. ROBOT-BASED MANUFACTURING OF HIGH-PRESSURE COMPOSITE VESSELS

A typical robotic platform for automated winding of the composite tape is presented in Fig. 2. Here, the vessel liner to be covered by the thermoplastic reinforcement is manipulated by the positioner, which is able to change its orientation in order to improve accessibility of certain zones by the technological tool. This tool is attached to the robot flange and ensures placement of the tape reinforcement in desired locations. The robot is installed on a translational linear track allowing adjusting its base location while processing relative large products.

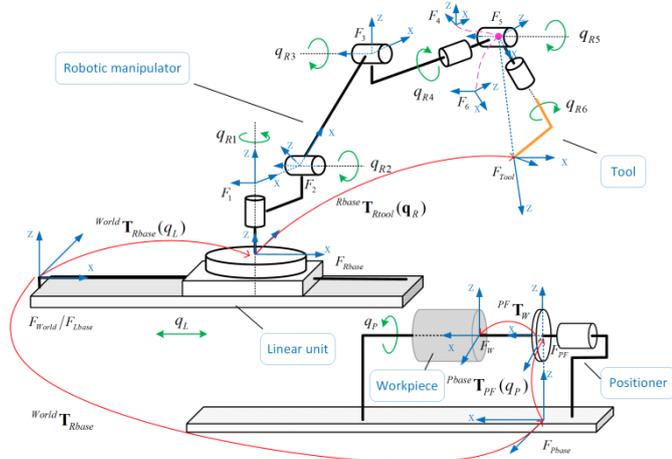


Fig. 2. Robotic workcell for manufacturing of high-pressure composite vessel

In robot-based high-pressure composite vessel fabrication, preparation of the manufacturing process includes a number of stages presented in Fig. 3, where the motion coordination of all robotic system components is one of the most difficult procedures. Within this process, the desired winding path is generated using a dedicated CAM system and it is presented in a discrete form (as an augmented line, usually). Further, the obtained set of task points is transformed into the task graph that describes all possible combinations of the robot, positioner and linear track coordinates. Then, the motion generator produces the optimal trajectories that correspond to the “shortest” path on the task graph. Finally, the obtained

motions are converted into the program for the robot control system. More details concerning these procedures can be found in (Gao, 2018).

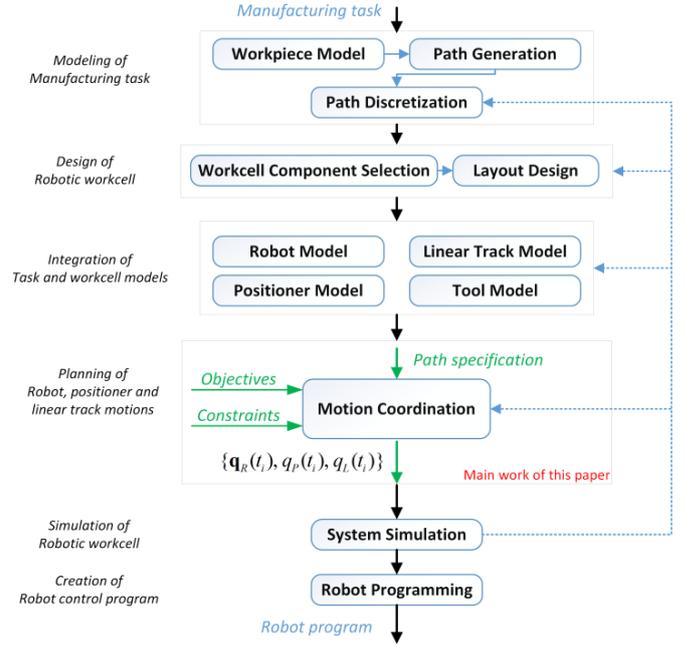


Fig. 3. Manufacturing process preparation for high-pressure composite vessel.

3. KINEMATIC MODEL OF THE ROBOTIC TAPE WINDING SYSTEM

To describe the winding task, let us present it as a sequence of the frames $\{F_{task}^{(i)}, i=1,2,\dots,n\}$, in such a way that the X-axis is directed along the path direction and Z-axis is normal to the workpiece surface pointing outside of it. Using these notations, the task locations can be described by a set of 4×4 homogenous transformation matrices and the considered tape winding task is formalized as follows:

$${}^w\mathbf{T}_{task}^{(1)} \rightarrow \dots \rightarrow {}^w\mathbf{T}_{task}^{(i)} \rightarrow \dots \rightarrow {}^w\mathbf{T}_{task}^{(n)}; i=1,2,\dots,n \quad (1)$$

where all vectors of positions and orientations are expressed with respect to the workpiece frame (see superscript “w”). To execute the given winding path, the technological tool must sequentially visit the frames (1) as fast as possible.

In any task location, the spatial configurations of the robot, positioner and linear track can be described by the joint coordinates \mathbf{q}_R , q_p and q_L . So, the task locations can be expressed using the direct kinematic functions of these components, which are further denoted as $g_R(\mathbf{q}_R)$, $g_p(q_p)$ and $g_L(q_L)$. This allows us to write the kinematic equations describing the given winding task in the following form

$$\begin{aligned} {}^{World}\mathbf{T}_{Lbase} \cdot g_L(q_L^{(i)}) \cdot g_R(\mathbf{q}_R^{(i)}) \cdot {}^{Tool}\mathbf{T}_{task} &= \\ &= {}^{World}\mathbf{T}_{Pbase} \cdot g_p(q_p^{(i)}) \cdot {}^w\mathbf{T}_{task}^{(i)}; i=1,2,\dots,n \end{aligned} \quad (2)$$

where all notations are defined in Fig. 2. It is clear that the above equations cannot be solved for \mathbf{q}_R , q_p and q_L in unique way because the robotic system is kinematically redundant. On the other side, it gives some freedom for

optimization of the coordinated motions of the robotic manipulator with the positioner and linear track movements.

4. GENERATION OF OPTIMAL MOTIONS FOR ROBOTIC MANIPULATOR AND POSITIONER

To present the problem of optimal motion generation in a formal way, let us define the function $\mathbf{q}_R(t)$, $q_p(t)$ and $q_L(t)$ describing profiles of the robot, positioner and linear track joint coordinates as functions of time $t \in [0, T]$. Additionally, let us introduce a sequence of time instants $\{t_1, t_2, \dots, t_n\}$ corresponding to the cases when the technological tool visits the task locations (1). It allows presenting the considered optimal motion coordination problem as

$$\begin{aligned}
 & \text{find} \\
 & \{ \mathbf{q}_R(t_i), q_p(t_i), q_L(t_i) \mid i = 1, 2, \dots, n \} \\
 & \text{such that} \\
 & T \rightarrow \min_{\mathbf{q}_R(t), q_p(t), q_L(t)} \\
 & \text{s.t.} \\
 & {}^{World} \mathbf{T}_{Lbase} \cdot g_L(q_L(t_i)) \cdot g_R(\mathbf{q}_R(t_i)) \cdot {}^{Tool} \mathbf{T}_{task} = \\
 & \quad \quad \quad = {}^{World} \mathbf{T}_{Pbase} \cdot g_p(q_p(t_i)) \cdot {}^W \mathbf{T}_{task}^{(i)} \quad (3) \\
 & \mathbf{q}_{R,P,L}^{\min} \leq \mathbf{q}_{R,P,L}(t_i) \leq \mathbf{q}_{R,P,L}^{\max} \\
 & \dot{\mathbf{q}}_{R,P,L}^{\min} \leq \dot{\mathbf{q}}_{R,P,L}(t_i) \leq \dot{\mathbf{q}}_{R,P,L}^{\max} \\
 & \ddot{\mathbf{q}}_{R,P,L}^{\min} \leq \ddot{\mathbf{q}}_{R,P,L}(t_i) \leq \ddot{\mathbf{q}}_{R,P,L}^{\max} \\
 & \text{cond}(\mathbf{J}(\mathbf{q}_R(t_i))) \leq C_{\max} \\
 & \text{colls}(\mathbf{q}_R(t_i), q_p(t_i), q_L(t_i)) = 0 \\
 & \text{where} \\
 & t_1 = 0, t_n = T; \quad i = 1, 2, \dots, n
 \end{aligned}$$

where the main objective is to minimize the total motion time using full capacities of the redundant robotic system, which are limited by the maximum velocity/acceleration values for the actuated joints. Besides, the collision constraints $\text{colls}(\cdot)$ as well as the distance to singularities $\text{cond}(\cdot)$ are also taken into account.

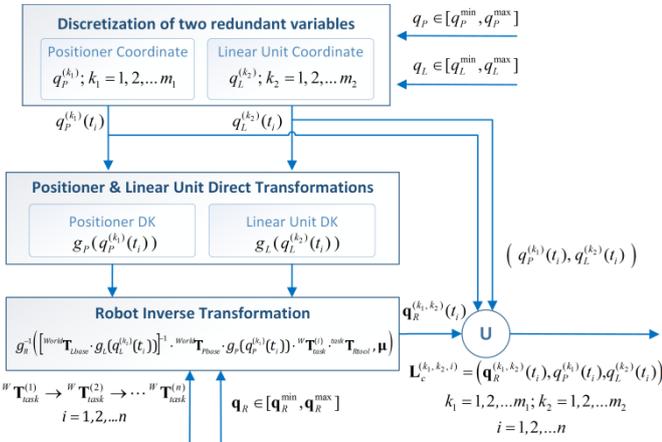


Fig. 4. Transformation of the original continuous problem into discrete form.

Because of specific constraints, the above presented continuous optimization problem cannot be solved in a

straightforward way. For this reason, the considered problem is converted into a discrete form by sampling the redundant variables corresponding to the positioner and the linear track. Then, using ideas proposed in our previous work (Gao et al., 2017b) and applying sequentially the direct kinematics of the positioner and linear track as well as the inverse kinematics of the robot, one can get the configuration states for the robotic system in joint space (see Fig. 4). This allows generating an extended task graph where all task locations are ordered in time. This graph contains all possible configurations of the considered robotic system for executing the given tape winding path, and the desired time-optimal solution of the relevant optimization problem is presented as the shortest path connecting the initial and the final layers.

The structure of this 3D graph is presented in Fig. 5 where the nodes $\{\mathbf{l}_{task}^{(k_1, k_2, i)}, \forall k_1, \forall k_2\}$ correspond to the i^{th} task location ${}^W \mathbf{T}_{task}^{(i)}$ and the indices (k_1, k_2) are related to the sampled coordinates of the positioner and linear track respectively.

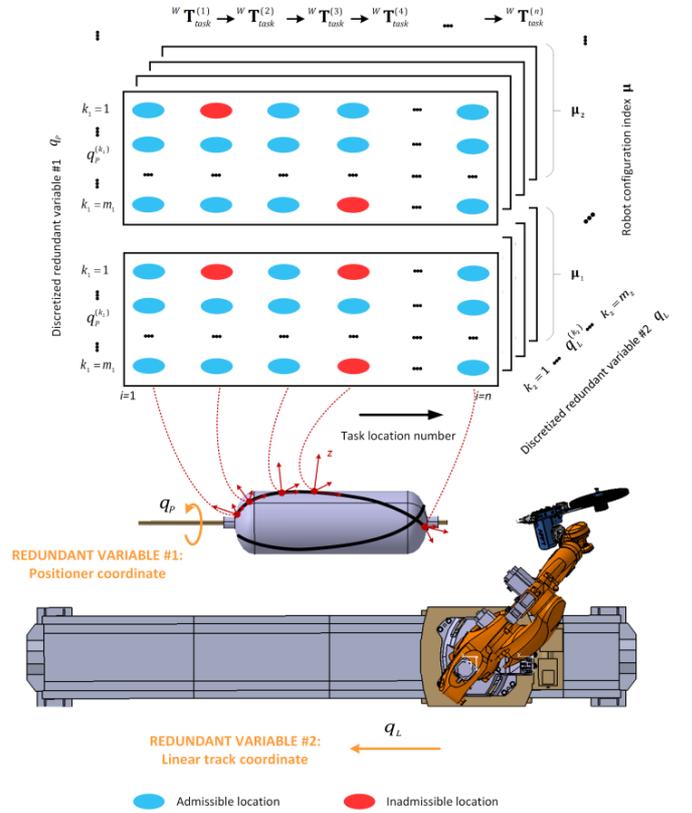


Fig. 5. Task graph corresponding to the motion generation problem with two redundant variables.

Using such presentation, the original continuous problem (1) is converted into a specific shortest-path problem on the graph, where all three successive nodes satisfy the acceleration constraints and the distances between two nodes $\mathbf{l}_{task}^{(k_1, k_2, i)}$ and $\mathbf{l}_{task}^{(k_1, k_2, i+1)}$ are equal to the technological tool displacement time from the i^{th} to the $(i+1)^{\text{th}}$ task point, which is restricted by the maximum velocities and accelerations of the robot, the positioner and the linear track. It should be also noted that some of the nodes are excluded from the graph because of violation of the collision or singularity constraints as well as the joint limits. These nodes are marked as

“inadmissible” ones in Fig. 5, and they are not connected to any neighbour. So, the objective function to be minimized (robot motion time) can be presented as the sum of the edge weights

$$T = \sum_{i=1}^{n-1} \text{dist}(\mathbf{L}_{\text{task}}^{(k_1^i, k_2^i, i)}, \mathbf{L}_{\text{task}}^{(k_1^{i+1}, k_2^{i+1}, i+1)}) \rightarrow \min \quad (4)$$

that are computed as

$$\text{dist}(\mathbf{L}_{\text{task}}^{(k_1^i, k_2^i, i)}, \mathbf{L}_{\text{task}}^{(k_1^{i+1}, k_2^{i+1}, i+1)}) = \max \left(\frac{|q_j^{(k_1^i, k_2^i, i)} - q_j^{(k_1^{i+1}, k_2^{i+1}, i+1)}|}{\dot{q}_j^{\max}} \right) \quad (5)$$

i.e. taking into account the maximum allowable velocities $\{\dot{q}_j^{\max}; j=1,2,\dots,8\}$ of the actuators. Corresponding optimal solution is represented by the sequence $\{\mathbf{L}_{\text{task}}^{(k_1^1, k_2^1, 1)}\} \rightarrow \{\mathbf{L}_{\text{task}}^{(k_1^2, k_2^2, 2)}\} \rightarrow \dots \rightarrow \{\mathbf{L}_{\text{task}}^{(k_1^n, k_2^n, n)}\}$ that contains the actuated coordinates of the robot, positioner and linear track. It worth mentioning that the above expression straightforwardly takes into account the velocity constraints, while the acceleration constraints are verified by means of the second order approximation applied to the corresponding functions $\mathbf{q}_r(t)$, $q_p(t)$ and $q_l(t)$ on the time interval $t \in [t_{i-1}, t_{i+1}]$. It allows us to present the acceleration constraints on the desired trajectory of the considered robotic system in the following form:

$$\frac{2|\Delta t_i \Delta q_j^{(i+1)} - \Delta t_{i+1} \Delta q_j^{(i)}|}{\Delta t_{i+1} \Delta t_i (\Delta t_{i+1} + \Delta t_i)} \leq \ddot{q}_j^{\max} \quad (6)$$

where $\Delta q_j^{(i)} = q_j^{(k_1^i, k_2^i, i)} - q_j^{(k_1^{i-1}, k_2^{i-1}, i-1)}$ and Δt_i are computed as the travel time between the nodes $\mathbf{L}_{\text{task}}^{(k_1^i, k_2^i, i)}$ and $\mathbf{L}_{\text{task}}^{(k_1^{i-1}, k_2^{i-1}, i-1)}$.

To find the desired optimal path, the conventional optimization techniques can be hardly applied because of extremely high computing time (Gao et al., 2017b). Besides, these techniques are not able to take into account the acceleration constraints that are very essential here. For these reasons, a dedicated problem-oriented algorithm has been developed for this problem. This algorithm is based on the dynamic programming principle, aiming at sequentially finding the shortest paths for the problems of lower dimensions, i.e. from $\{\mathbf{L}_{\text{task}}^{(k_1^1, k_2^1, 1)}, \forall k_1, \forall k_2\}$ to the current nodes $\{\mathbf{L}_{\text{task}}^{(k_1^i, k_2^i, i)}, \forall k_1, \forall k_2\}$. If the length of the corresponding shortest path is denoted as $d_{k_1, k_2, i}$, then the shortest path for the next locations $\{\mathbf{L}_{\text{task}}^{(k_1^i, k_2^i, i+1)}, \forall k_1, \forall k_2\}$ can be obtained by combining the optimal solutions for the previous column $\{\mathbf{L}_{\text{task}}^{(k_1^i, k_2^i, i)}, \forall k_1, \forall k_2\}$ and the distances between the task locations with the indices i and $i+1$,

$$d_{k_1, k_2, i+1} = \min_{k_1', k_2'} \left\{ d_{k_1', k_2', i} + \text{dist}(\mathbf{L}_{\text{task}}^{(k_1, k_2, i+1)}, \mathbf{L}_{\text{task}}^{(k_1', k_2', i)}) \right\} \quad (7)$$

This expression is applied recursively, starting from the second layer of the task graph ($i=2$) and finishing by the last one ($i=n$). So, the desired optimal path can be obtained after selection of the minimum length $d_{k_1, k_2, i+1}$ corresponding to the last layer. It should be mentioned that this algorithm can be also simplified to a one redundant variable case by fixing the robot base on the linear track, when the workpiece is small.

5. INDUSTRIAL IMPLEMENTATION OF GENERATED OPTIMAL MOTIONS

To demonstrate advantages of the proposed technique, let us apply it to an industrial problem that deals with fabrication of a composite vessel with the maximum pressure of 500 bar. The considered high-pressure vessel is composed of a cylindrical part and two elliptical domes at both ends of the cylinder (see Fig. 1). The cylinder has the diameter of 168 mm and the length of 400 mm. The domes have the depth of 40 mm. The vessel is covered by several layers of the thermoplastic tape, which are wound by the robot following certain patterns and consolidated in situ.

The winding patterns were generated using the dedicated software Composicad. For winding of the considered pressure vessel, there are two basic types of lamina: helical and circumferential. The helical winding is typically lower than 54° , whereas the circumferential one is usually done at an angle close to 90° (Vasiliev, 2009, Shen, 1995). After all of the helical and circumferential laminas are placed on the vessel surface, a connector lamina could be also added to join them. In this work, the developed motion generation technique was applied to the two basic types of lamina.

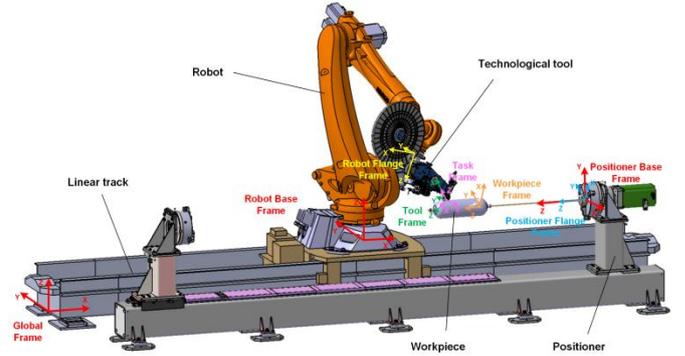


Fig. 6. Robotic platform for automated thermoplastic tape winding process.

Relevant robotic tape winding workcell (Fig. 6) is composed of 6-axis serial robot KUKA KR210 R3100, 1-axis translational linear track KUKA KL2000 and 1-axis rotational positioner AFPT 550. Here, there are two extra degrees of freedom provided by the positioner and linear track. However, for the considered manufacturing task that deals with rather small vessel, the robot can easily execute the tape winding process without changing its base location. Besides, the minimum travel distance of the linear track is comparable with the vessel size. So, for this product, there is no reason to activate the linear track during the winding.

5.1 Task #1: A helical winding path

The first task deals with a helical winding lamina. A sample of the path locations ensuring a single circuit helical winding was created using Composicad. Relevant data contain the description of a discrete 3D-augmented curve. They include Cartesian positions and normal directions of the winding path with respect to the workpiece frame as shown in Fig. 7.

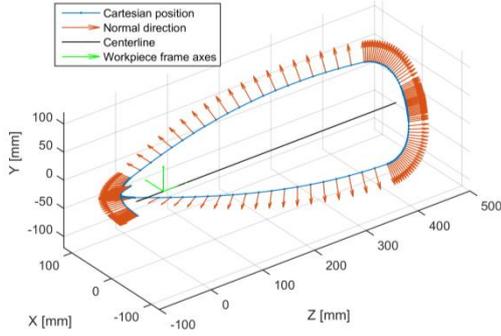


Fig. 7. Discrete representation of the helical winding path in the form of the augmented line.

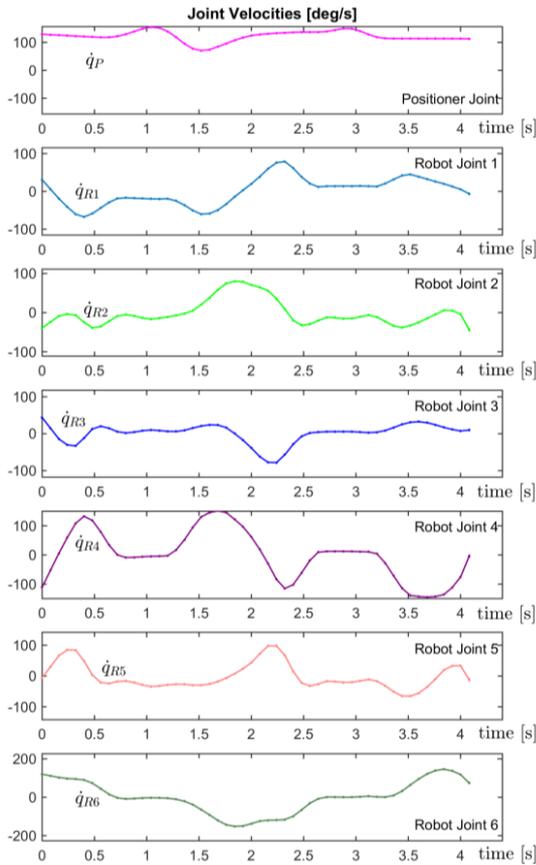


Fig. 8. Time-optimal velocity profiles for Task #1.

To generate the time-optimal coordinated motions of robotic manipulator and positioner, the joint coordinate spaces of the positioner was discretized with the step of 1° . Then, the proposed time-optimal motion generation technique was applied for the case of a single redundant variable. Relevant computational results are presented in Fig. 8. As follows from them, the developed technique allows generating time-optimal helical winding trajectory in manufacturing of the vessel with the minimum motion time 4.2 s, which is almost 3 times better than the result provided by Compositcad.

5.2 Task #2: A circumferential winding path

The second task deals with a circumferential winding lamina. A sample of the path locations ensuring a single circuit circumferential winding was created in a similar way. The relevant discrete 3D-augmented curve is shown in Fig. 9.

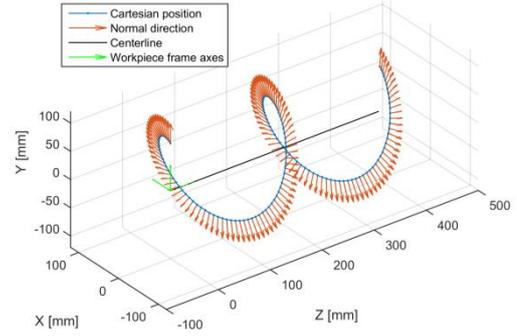


Fig. 9. Discrete representation of the circumferential winding path in the form of the augmented line.

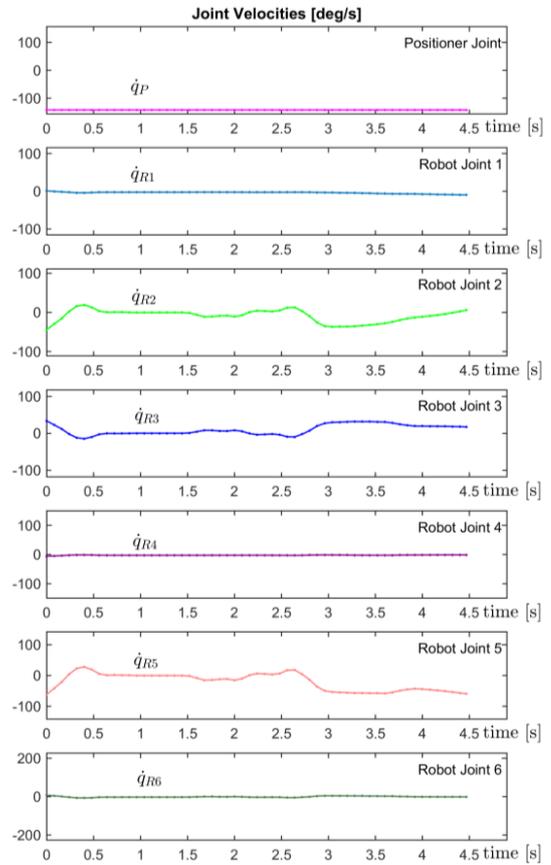


Fig. 10. Time-optimal velocity profiles for Task #2.

By sampling the joint coordinate spaces of the positioner with the step of 1° , the developed time-optimal motion generation technique for the case of a single redundant variable was applied again. Relevant computational results are presented in Fig. 10. As follows from them, the developed technique allows generating time-optimal circumferential winding trajectory in manufacturing of the composite vessel with the minimum motion time 4.5 s.

It should be mentioned that after discrete optimization, a dedicated smoothing technique might be also used to locally improve the velocity and acceleration profiles and ameliorate the actuator working conditions.

The above presented algorithm was tested using Matlab 2016b environment (running at Intel®i5 CPU@2.67GHz

2.67GHz). It took about one minute to generate the time-optimal motions for each task.

6. CONCLUSIONS

This paper presents a technique dealing with the optimal motion coordination in redundant robotic tape winding systems for manufacturing of high-pressure composite vessels. In contrast to previous results, this work focuses on generation of the time-optimal coordinated motions for the two basic types of winding lamina, i.e. helical and circumferential. In the frame of the developed technique, the original continuous optimization problem is converted into a combinatorial one where the desired time-optimal motions are presented as a specific shortest path on the task graph. Then, the desired time-optimal motions are obtained using the developed enhanced dynamic programming algorithm that takes into account the actuator capabilities (coordinate limits, velocities and accelerations) as well as the kinematic and geometric constraints allowing avoiding collisions and singular configurations of the manipulator. The proposed technique is illustrated by industrial case studies dealing with two winding tasks (helical and circumferential curves). In future, this technique will be generalized for a connector lamina that allows transitions between the two basic types of lamina considered in this work.

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