REDUNDANCY RESOLUTION OPTIONS FOR THE TWIN-IT-ROMANS ROBOTIC HYBRID MANUFACTURING SYSTEM

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Abstract. The Twinnig Iztech in Robotics Manufacturing System (TWIN-IT-ROMANS) project funded by EU Horizon -Widera-2023-Access-02-01 aims to develop a hybrid manufacturing system that can perform additive and subtractive manufacturing processes and inline quality control using a robotic system. The system will incorporate a 6-degree-of-freedom robot arm and a positioner with 2-degree-of-freedom, which will operate synchronously. This manipulation system is to be designed for performing different manufacturing operations with different degrees-of-freedom requirements. In order to reveal alternative trajectory planning scenarios for this system, this paper presents an initial review of redundancy resolution approaches for kinematically redundant robotic manipulators. First, the four main approaches for redundancy resolution techniques are introduced. Then main studies on energy minimization and stiffness maximization for kinematically redundant robotic manipulators are reviewed. Similar or new approaches are planned to be generated and implemented for the redundant system for hybrid manufacturing.

Keywords: SDG9, Kinematic Redundancy, Hybrid Manufacturing, Energy Minimization, Stiffness Maximization.

1 Introduction

The Twinnig Iztech in Robotics Manufacturing System (TWIN-IT-ROMANS) project funded by EU Horizon -Widera-2023-Access-02-01 aims to develop a hybrid manufacturing system that can perform additive and subtractive manufacturing processes and inline quality control using a robotic system. Two separate systems will be developed in Innsbruck and Izmir. The system at Innsbruck will aim to manufacture parts with thermoplastic materials and the system at Izmir will aim to manufacture parts with composite materials, whereas the subtractive manufacturing comprises drilling and milling of the produced part with additive manufacturing. In this consortium, RWTH Aachen University and Izmir Institute of Technology teams will collaborate for formulating the trajectories of the hybrid manufacturing system's additive and subtractive processes.

Both systems will incorporate a 6-degree-of-freedom (DoF) robot arm and a 2-DoF positioner (Fig. 1). Both parts will operate synchronously, which will result in a redundant system with a total of 8-DoF. Considering the tasks, the number of redundant DoF changes. For example, for the additive manufacturing tasks generally the required DoF ranges from 3 to 6 depending on the manufacturing methods and the geometry of the workpiece. When we consider the machining operations in 3D tasks, such tasks call for only 5-DoF if the rotation of the drilling/milling axis is not required to be controlled. Therefore, when considering the tasks, the number of redundant DoF ranges from 2 to 5 DoF.

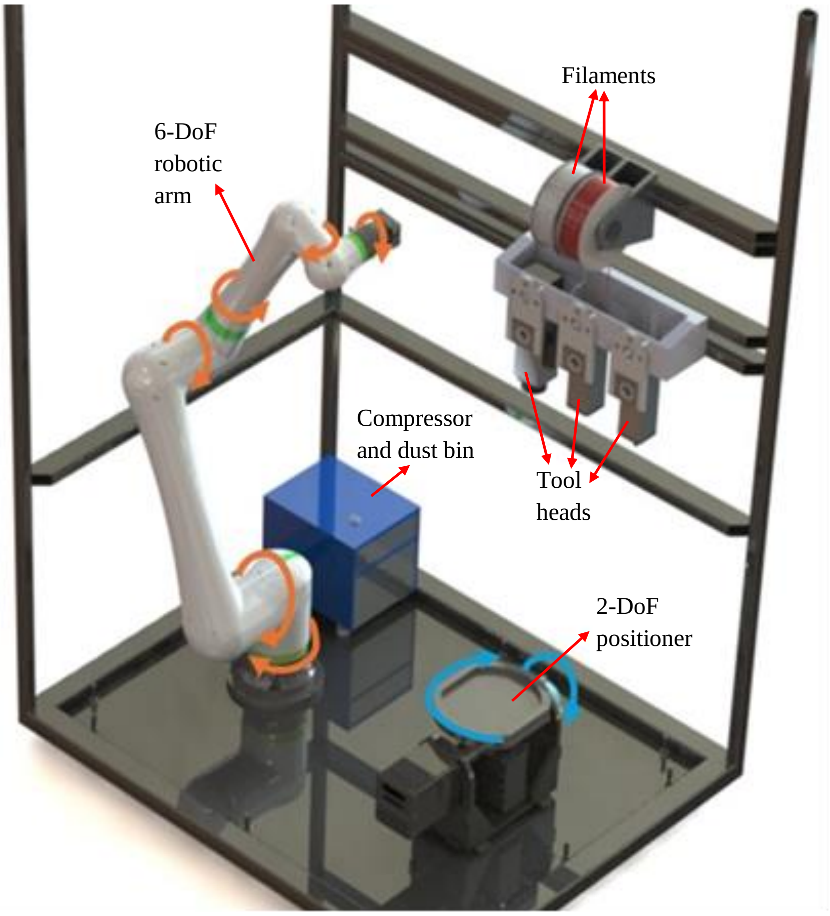

Fig. 1. Conceptual illustration of the robotic system

The redundant DoF gives us the chance to select from an infinite number of solutions the one that meets some additional considerations. These considerations are usually about energy efficiency [1], minimization of joint motion [2], singularity avoidance [3], etc. To optimize for these additional considerations, various redundancy resolution algorithms exist. These algorithms are introduced briefly in Section 2.

To our knowledge, there are no studies related to hybrid manufacturing systems using the concept of redundant robot manipulation. Different manufacturing tasks may require different redundant DoF values, different optimization objectives and techniques. One of the main interests in using a redundant system in our hybrid manufacturing system is to minimize energy consumption while performing the designated additive manufacturing process. In additive manufacturing, the major source of energy consumption warming up and maintaining the temperature of the material and the built table, but there is also considerable amount of energy requirement due to the motion of the manipulator [4]. There is no physical interaction with the environment for the additive manufacturing task. However, this is not the case when performing machining operations. The tool head comes into physical contact with the workpiece and exerts forces/moments. Rather than energy minimization, the priority in such a task is to ensure the precision of operation under these external loads. Therefore, the main interest for the subtractive manufacturing task is chosen to maximize the stiffness of the robotic system along the directions where forces/moments are applied.

Designing a hybrid manufacturing system capable of performing multiple operations within a single platform offers a highly efficient approach that aligns with several Sustainable Development Goals (SDGs). Goal 9—which focuses on building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation—is supported by this project. Target 9.5 emphasizes the importance of technological development and research, which this project addresses through the innovative use of robotic system redundancy to adjust stiffness for specific tasks, such as those involved in subtractive manufacturing.

The system's redundancy is also utilized for energy minimization as a secondary task alongside its primary role in additive manufacturing. This dual-functionality feature supports SDGs Goal 7, Goal 9, and Goal 12. Goal 7 seeks to ensure access to affordable, reliable, sustainable, and modern energy; the TWIN-IT-ROMANS project advances this goal, particularly Target 7.3, by improving energy efficiency in its production methods. Additionally, Goal 9, through Target 9.4, promotes increased resource-use efficiency, which this project aims to achieve. Finally, Goal 12 focuses on sustainable consumption and production, with Target 12.2 emphasizing the efficient use of natural resources. The project's commitment to reducing energy consumption and resource usage thus directly contributes to these SDGs.

In summary, this paper introduces the concept of a redundant robotic system for hybrid manufacturing and its relation with SDGs with an initial review on redundancy resolution approaches for energy and stiffness optimization. Section 2 provides an overview of optimization techniques, focusing on those applied in kinematically redundant robots. Section 3 discusses various optimization strategies for energy minimization, while Section 4 introduces algorithms designed to maximize stiffness for use in subtractive manufacturing. Section 5 concludes the paper.

2 Optimization (Techniques) of Redundant System

Redundancy is a concept observed across various fields, both within and beyond engineering. One type of redundancy, known as kinematic redundancy, pertains specifically to the DoF of a mechanism, robot, or similar system. Kinematic redundancy occurs when the DoF of a mechanism or robot exceeds the DoF required to accomplish a specified task. In such cases, an infinite number of possible solutions arise for performing the primary task. Kinematic redundancy is especially advantageous when a secondary task is introduced, as it allows the system to select the most appropriate solution for this additional objective from the multitude of solutions generated for the main task.

There are various optimization tools and techniques to identify the optimal solution. One of these tools is intelligent algorithms. Intelligent algorithms constitute another category of optimization methods, with Particle Swarm Optimization (PSO) and genetic algorithms being notable examples. These algorithms are applied to address inverse kinematics in redundant robotic arms, aiming to achieve optimal configurations [5]. In such studies, the problem is formulated as a mini-max optimization problem to effectively explore feasible solutions. The other tool for optimization is machine learning. Machine learning tools offer a powerful approach to optimizing kinematic solutions. This technique improves convergence speed and solution accuracy in robotic systems, thus enhancing overall performance [6].

In addition to these tools, there are various techniques frequently used for optimization. Depending on the desired sub-task, conditions, and needs, these techniques can be used in redundant systems. Examples of these techniques are control decoupling, pseudoinverse, task-space, and null-space optimization.

Control decoupling is an optimization method used for the control of redundant systems. It simplifies the control process by separating the control of different degrees of freedom of the system. In other words, it reduces the complexity of complex control problems by dividing them into sub-problems. Since each component is controlled separately, it provides a faster response to environmental changes. This also directly affects the performance of the system [7]. Pseudoinverse is an optimization method used to optimize criteria such as minimizing joint motion and avoiding obstacles. This technique allows the calculation of joint velocities that obtain the end-effector speed. It is also one of the techniques that can be used to ensure that joint velocities are constant and stable. This optimization technique can be used in real-time applications because of its efficiency [8]. Task space division is another optimization technique that can be used in redundant robotic systems. This technique gives more consideration to end-effector trajectories and performance of macro/micro manipulation [9]. One of the optimization techniques that is quite effective for providing motion control and executing assigned tasks is the null-space approach. This method is an optimization technique that allows sub-tasks to be performed while executing the main task. The configuration set that does not affect the main task is called null space. The Jacobian matrix is used for defining the null space of the manipulator [10].

3 Energy Minimization for Additive Manufacturing Tasks

The primary task of this algorithm is to carry out the additive manufacturing task and its secondary task is planned to minimize energy consumption by the system. The secondary task contributes to SDG 7 by addressing Target 7.3.

There are several approaches to minimizing energy consumption in robotic systems. One of the primary methods is motion planning, which has a direct impact on energy use. During robotic operations, each arm movement is executed by one or more active joints. These joint movements, driven by actuators, require energy. Therefore, the more the arm moves, the more energy is consumed. By minimizing unnecessary movements, energy expenditure can be reduced, making motion planning an effective strategy for conserving energy. Research in this area has focused on developing optimization methods to minimize redundant or inefficient motions in robotic arms [11].

Another approach to minimizing energy consumption involves a method based on motion planning that takes gravitational forces into account. This technique aims to reduce the work performed by the robot arms against gravity, thus minimizing the energy required by the actuators. By aligning movements to work with rather than against gravity, the energy used by the robot's actuators is conserved, preventing unnecessary conversion to potential energy. As a result, significantly less energy is expended on the same task [12].

These minimizing energy methods relate to any robotic system, redundant or non-redundant. The redundancy resolution techniques mentioned in section 2 can be used to minimize a certain objective function related to energy for redundant systems. Four redundancy resolution techniques are mentioned in section 2. Using these techniques, the desired energy-saving task can be integrated into the system.

The first optimization method mentioned in Section 2 was control decoupling. The load carried by each joint is different than the other. The energy spent on the work to be done varies according to the loads they carry. The movements of the joints that carry more load than the other joints can be restricted after reaching a certain position and then the other joints in the system are controlled as if they were a non-redundant system. The pseudo-inverse method used in redundant systems allows to distribute the workload among the joints and the joints that move higher inertia can be selected to move the least and thus, energy can be saved. Another redundancy resolution method, the null-space method, can also be used for this sub-task. In this case, the target function defined for the secondary task needs to be defined as the total energy spent during the manipulation and has to be minimized.

In conclusion, even though the manipulation system is non-redundant path planning energy can be saved and this saving can be further enhanced having a kinematically redundant setting as a result of synchronous motion of the 6-DoF manipulator and the 2-DoF positioner. Commonly used methods for path planning can be focused on as the initial methodology to save energy. In addition, redundancy resolution techniques that enable the optimization of energy use can be deployed for further improvements on minimizing the energy spent while performing additive manufacturing tasks.

4 Maximizing Stiffness through Configuration for Subtractive Manufacturing Tasks

The common problem in using robot manipulator for subtractive manufacturing is the need for the manipulator to exert forces to the workpiece. While force control is a challenge, the focus of this paper is to use the redundancy of the manipulation system to enhance the precision of the operation. Precision of manufacturing tasks generally calls for rigidity of the manufacturing systems which are usually CNC systems having highly stiff axes. A robot manipulator with revolute joints suffers in terms of rigidity when compared to the CNC machines.

The abovementioned downsides of using robot manipulators for subtractive manufacturing processes may be compensated by adjusting the stiffness characteristics of the manipulator. This option is very limited for a sufficient manipulator having up to 8 configurations. However, when a kinematically redundant system is considered, this option can be realized by appropriate selection of the secondary task. This secondary task in this case is regulating the stiffness of the manipulator along the directions where forces are transferred to the workpiece.

Choi et al. addressed the stiffness control of redundant manipulators through the joint stiffness analysis and joint stiffness control scheme, called Orthogonal Stiffness Decomposition Control. They presented a generalized stiffness model between the joint and task space stiffness which shows the existence of the additional stiffness concerning the configuration change and force [13]. Müller used kinematic redundancy to generate internal preload that would not interfere with the task. This preload is controlled in order to achieve a desired end-effector stiffness, i.e. a desired relationship of applied forces and resulting displacements. This active stiffness yields immediate counteractions to load variations and thus strengthens the integrity of the manipulators. Differential end-effector stiffness is defined, and a stiffness control scheme is proposed [14].

Other than redundancy based on the explicit stiffness enhancement resolution methods, another possibility is to use the relation between the stiffness and velocity-level singularity relations. When the manipulator approaches these singularity conditions, in one direction the motion capability of the manipulators suffers. In fact, along that direction, the stiffness of the manipulator reaches its highest values. This phenomenon can be used when the manipulator is required to exert forces along the normal of the work-piece’s surface. There are many studies in the literature on singularity avoidance using redundancy resolution techniques [3, 15, 16]. These methods can then be used to move towards singularities in the directions where physical interaction needs to occur between the tool head held by the robot and the workpiece.

In conclusion, although robot manipulators are not actually the best choice for precise subtractive manufacturing operations, kinematic redundancy can enhance their performances. The appropriate selection of the secondary task either formulated to increase the stiffness of the manipulator or moving towards singularities along a certain direction may be employed for such operations.

5 Conclusion

This paper presents a review of redundancy resolution approaches for a hybrid manufacturing system that incorporates a kinematically redundant robotic system with a specific emphasis on energy minimization and stiffness maximization. We have shown the possible and new approaches to be generated and implemented having SDG in mind for this new hybrid manufacturing system. Selection and implementation of proper optimization objectives and techniques remain as future work of the TWIN-IT-ROMANS project.

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