Human-Robot Task and Motion Planning in an Industrial Application

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I. INTRODUCTION

Human-Robot Collaboration (HRC) has emerged as a significant technological challenge in the industrial landscape in recent years. By combining the precision, efficiency, and repeatability of robots with the intelligence, adaptability and expertise of humans, numerous advantages emerge. Such collaboration reduces operator fatigue, improves ergonomic conditions, and enhances production quality [1], [2]. Proper integration of Task and Motion Planning (TAMP) [3], considering both the environment and user needs is essential to maximise the benefits of robot-assisted tasks and to ensure safety in collaborative tasks.

Since an industrial environment shared by humans and robots is a highly dynamic scenario, many manufacturing industries have not yet introduced automation in their processes. The unpredictability of human presence must be integrated into TAMP and robot control, leveraging the latest advances in perception and interactions. Focusing on TAMP, the challenges such a framework must address include:

CHL1 Integration of the knowledge of humans' and robots' capabilities.
CHL2 Computation of a feasible actions sequence and sharing them between humans and robots.
CHL3 Robot movements must satisfy ergonomic constraints and be synchronized with humans.
CHL4 Ensuring human safety during robot motion.
CHL5 Constant monitoring of the scene with online adaptation by the robot to any changes.

These five challenges can be grouped into three macro categories: collaboration (CHL1-3), safety (CHL4) and monitoring (CHL5). Firstly, CHL1 calls for the seamless integration of human and robot capabilities, emphasizing the need to harness their expertise effectively. CHL2 extends this by highlighting the intricate task of computing a viable action sequence and facilitating its sharing between human and robot counterparts, which is pivotal for synchronized and efficient collaboration. CHL3 complements these by emphasizing the ergonomic alignment of robot movements with human actions, particularly vital in cooperative endeavours involving physical interaction. Moving on to safety, CHL4 addresses the paramount issue of ensuring human safety throughout robot motion, necessitating robust safety mechanisms and real-time risk assessment. Lastly, the theme of monitoring comes to the fore with CHL5, stressing the robot's continuous scene observation and adaptive response capabilities to address environmental changes proactively.

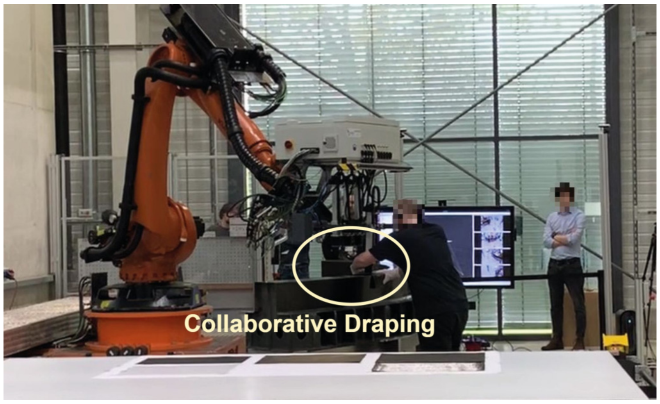

Fig. 1: Example of carbon fiber draping process in a HRC.

A common technique in TAMP is interleaving the symbolic and geometric search processes by calling a motion planner at each step and assigning geometric parameters to the currently symbolic state before proceeding. The interleaving becomes problematic when a planned state is valid in symbolic space, but geometrically infeasible. To address this, FFRob [4] introduced an FF-like heuristic that integrates geometric information into the FF-search. An alternative approach executes a geometric search on candidate symbolic plans [5]. Similarly, Dantam et al. [6] incrementally generate symbolic plans using an incremental Satisfiable Modulo Theory solver, invoking a motion planner for validation. Most TAMP methods have long processing time and consider a static environment, assuming an ideal, noise-free perception system. Migimatsu and Bohg [7] introduced a TAMP formulation based on object-centric frames that work with reactive controllers. Nouman et al. [8] proposed a hybrid condition planner that extends the classical condition planner by integrating feasibility checks into the conditions of action. Castaman et al. [9] solve TAMP problems in a changing environment with a receding horizon approach, iteratively solving a reduced planning problem over a receding window. However, the approaches described above can be improved for industrial HRC scenarios. Thus, this paper tries to offer an approach that could enhance TAMP to solve some of the challenges outlined above for manufacturing processes.

One specific industrial scenario where a human-aware TAMP solution can play a critical role is in the carbon fiber draping process. This process is predominantly manual, carried out by skilled human operators whose expertise is essential for the final product's high quality. Draping involves

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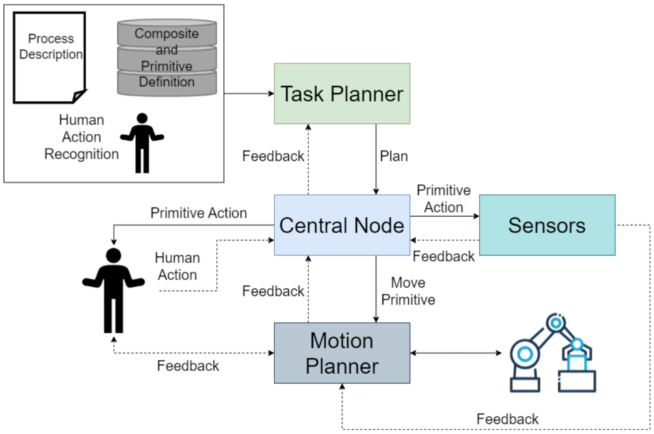

Fig. 2: Dynamic Human-Aware TAMP Framework [11].

transporting the carbon ply onto the mould and shaping it to fit. Another vital process is visual inspection to ensure product quality.

This challenge is being tackled by the EU project DrapeBot (`https://www.drapebot.eu/`), aiming to develop an HRC system that aids operators in carbon fibre draping. Within DrapeBot project, we are developing a TAMP approach (Fig. 2) to address the challenges of a dynamic human-aware industrial scenario.

In particular, it focuses on the dynamic scheduling of shared human-robot activities within a manufacturing environment where humans and robots have to collaborate to complete complex tasks like draping [10].

II. CONCEPT

In HRC industrial applications, the TAMP framework is pivotal. It must ensure flexibility in managing work plans, effectively address operator interventions, handle inputs from external sensors (e.g., perception systems and laser scanners), and safeguard operator safety. Furthermore, it should maintain production quality by automating inspection processes for quality control. Employing TAMP enhances industrial processes, making them more productive and enabling efficient utilization of resources and operator expertise.

Our proposed framework (Fig. 2) consists of three main modules: Task Planner, Motion Planner and Central Node.

The **Task Planner** [11] orchestrates the operations of humans and robots. It generates a continuously updated plan that will serve as a workflow guideline and consist of the sequence of actions to complete the assigned task. The Task Planner handles human interrupts [12], dynamically adjusting the computed plan to satisfy collaboration needs or to deal with unexpected events (*CHL1, CHL2*). Additionally, it employs recovery procedures to revert to a safe state. Since the planner has to deal with different agents, the effort must be divided in such a way that the robot maximizes its contribution and takes care of the heaviest actions (e.g. inspection, small plies transportation) so that the user can minimize his effort and concentrate more on the activity of draping the ply on the mould (*CHL2*). Thus, a three-tier hierarchical design enhances modularity and adaptability:

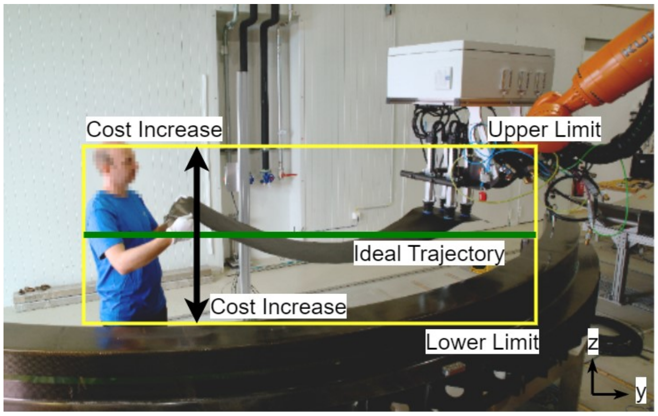

Fig. 3: Description of the cost function for the ergonomics motion planner.

- *Primitive actions*: Fundamental operations (e.g., Move, Draping, Inspection, etc.).
- *Composite actions*: Sequences of primitives for complex actions like patch transportation, involving robot movement, carbon fibre detection, etc.
- *Final Plan*: Provides a high-level view of the draping process by laying out the entire sequence of tasks for both human and robot agents.

The **Motion Planner** computes collision-free trajectory for robots. To ensure operator safety (*CHL4*), *Safe Zones* are introduced to restrict robot entry, assuring operator freedom. Motion planning algorithm considers these zones to compute non-collaborative motions. The collaborative trajectory is the most challenging to compute. The planner must take into account human limitations, emphasizing ergonomic constraints based on operator stature (*CHL3*). A skeletal tracking system [13] makes possible to compute an ergonomic trajectory that all agents can execute.

In the classical approaches, Task and Motion planner modules communicate directly to exchange information. However, due to the large amount of data to be handled from the industrial scene and process, our framework provides a **Central Node** to integrate and optimize task and motion planner modules. The plan is carried out by the Central Node, which also controls and supervises the proper primitives' activity. Additionally, this module constantly monitors the condition of the workcell using the sensors in the environment (*CHL5*). The Central Node also handles human gestures used to trigger action not foreseen in the plan (*CHL1*). In that case, it sends the information to the Task Planner module which is in charge of creating a new plan where the requested action is the first action to be performed.

III. CONCLUSIONS

In this paper, we examine the limitations of the traditional TAMP approaches in HRC scenarios. They could be improved to manage efficiently the dynamism and uncertainty introduced by users into an industrial HRC process. We identify and discuss the challenges the TAMP framework should address: integration of agents' capabilities, sharing activities with agents, ensuring operator's safety and ergonomics during collaborative motion and, finally, monitoring the environment and the process. These challenges are made explicit within the carbon fibre draping process as a real-world example. Finally, we describe the ongoing TAMP method to address these industrial challenges: the Task Planner computes the process plan taking into account the human and robot abilities; the Motion Planner computes trajectories both ensuring human safety (using the *Safe Zones* concept) and human ergonomics; the Central Node monitors the scene, the process and the operator's request.

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