Planning Safe Collaborative Behaviors through Risk-Aware Heuristic Search

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Abstract
Deploying collaborative robots in manufacturing presents diverse challenges. Rapid adaptability to the environment while ensuring user safety and engagement is paramount. Existing human-aware task sequencing solutions often lack explicit risk modeling and management. International standards emphasize severity, exposure, and avoidance as critical risk factors. To enhance intelligent risk awareness control, we propose integrating multiple risk factors into task sequencing models. This forms the basis for a cutting-edge planning framework-backed risk-aware task sequencing system. Our approach's evaluation across various scenarios showcases its efficacy and adaptability to diverse risk levels. Experimental results show a positive equilibrium between productivity and safety, achieving both high throughput and low operator risk.

Keywords
Task Planning and Scheduling, Human-Robot Collaboration, Artificial Intelligence

1. Introduction

The use of cobots in manufacturing environments allows for automating demanding, hazardous, and repetitive tasks boosting the flexibility of manufacturing processes. Nevertheless, task coordination between humans and robots remains a critical issue for productivity. Human-Robot Collaboration (HRC) entails challenging safety issues as collaborative environments involve tight proximity between robots and human workers raising multiple challenges [2]. In order to endow collaborative robots (cobots) with the ability to quickly adapt their behaviors to the actual state of the environment and keep the user safe and engaged in the interaction, some human-aware task sequencing solutions have been proposed (e.g., [3]) where risk management is often not explicitly modeled. In this work, we propose a novel risk-aware model for human-robot coordination considering the main risk factors highlighted in international robotic standards (ISO 10218, ANSI-RIA R15.06-2012) to provide a more detailed representation of risks overcoming a flat description based on a single value expressing severity and probability, which may not

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capture the nuances hidden in a production scenario. Our model includes five flexible and general risk factors that can be applied to any HRC context. We also present a software prototype planner to reason over the different risk factors entailed by the execution of collaborative tasks and synthesize safe and efficient collaborative task plans. Specifically, we model HRC task assignment problems as human-aware task planning problems. A task planning system then generates task plans implementing sequences of actions to accomplish predefined production objectives [3]. This entails building a flexible temporal plan that transforms the initial state of a system into a desired goal state. AI planning algorithms utilize domain knowledge and search techniques to efficiently explore the space of possible plans to identify the most feasible solution. This model informs a heuristic-based search that optimizes task assignment by considering a multi-objective perspective based on safety and efficiency. The designed heuristics allow the planner to find safe plans without compromising the efficiency of HRC productions. Its most important feature involves evaluating the risk of a situation by taking into account what robots and humans are doing at the same time. We evaluated our planner with other strategies in simulated environments demonstrating improved task assignments, effectively balancing safety and efficiency.

2. State of the art

In HRC, ANSI-RIA R15.06-2012 standard is an adoption of pre-existing robot safety standards such as ISO 10218 which focuses on providing HRC cell designers with appropriate guidelines to help them improve the safety of collaborative cells. It provides some of the safety measures that should be used to ensure a safe collaborative environment, such as safety stop, hand guiding, speed and separation monitoring, power and force limiting. The main risk factors in the standards, ranked by importance, are severity, exposure, and avoidance. These factors provide a more detailed representation of risk compared to the flat values based on severity and probability. By taking into account these factors, a comprehensive assessment of risk level can be conducted, resulting in categorizations such as negligible, low, medium, high, and very high. Standards provide suggestions also on how using these factors during the design of an HRC cell to reduce the risks. Focusing on a robot control perspective, safety measures are about assigning tasks to the robot and controlling its motions in order to reduce the risk of collisions with the operator while keeping a low cycle time.

HRC-oriented works usually focus on general design issues (see, e.g., [4, 5]) and on sub-problems such as scheduling human and robot actions (e.g., [6, 7]), or cooperative planning at a symbolic level (e.g., [8, 9]). Several works have investigated novel models and planning paradigms to enhance *human awareness* and realize more effective and safe robot behaviors in collaborative settings [10, 11]. A central aspect is the capability of enriching a symbolic task planning level with geometric information suitable to reason about spatial qualities of planned motions. The work [12] although not strictly correlated with human-robot interaction, shows an interesting combination of task and motion planning suitable to improve task planning with geometric reasoning and plan feasible motion trajectories. The interesting aspect of this approach is the pursuit of a "shared perspective" allowing task planners to reason on more realistic (geometry-aware) models. This is especially relevant in HRC where an explicit reasoning on the *qualities* of robot motions is crucial to enable safer and more effective behaviors.

The study [13] supports modeling multi-agent decision problems for human-aware task allocation. It uses a hierarchical task planning formalism to reason about structured decomposition and combined behaviors of multiple agents (e.g., human and robot) working together towards shared objectives (e.g., a production task [14]). However, this approach lacks explicit consideration of time constraints and action durations, limiting the effectiveness of generating optimal collaborative plans in terms of cycle time. The work [8] advances human-aware optimization by considering stochastic human dynamics. It creates a hierarchical model from single-agent demonstrations to capture task temporal relationships and prevent spatial conflicts in robot actions. Notably, this work combines safety and efficiency to improve planning decisions. The study [15] also combines stochastic human occupancy data in hierarchical collaborative modeling. It addresses task allocation, enabling robots to consider time constraints and human behavior for safe, efficient trajectory planning. The approach achieves a balance between safety and efficiency based on the agents' occupancy volumes. Another work [3] enhances simultaneous human-robot behaviors using a synergy matrix for parallel tasks. It employs a multi-objective planning formalism that successfully balances optimization and minimizes delays due to potential human-robot collisions. The study [16] introduces a new sequencing planning algorithm that optimizes cycle time while considering resource and safety constraints. Notably, it provides detailed safety reasoning by including constraints related to assembly/disassembly components.

In manufacturing-oriented methods, [17] optimizes the ergonomics of the human worker by using an online workflow scheduler. [18] and [19] proposed a TAMP framework for planning and executing tasks using first-order logic graphs. A contingent-based approach was proposed in [20], and [21] to deal with uncertainty on the outcome of actions. Although the mentioned works effectively address human-robot interaction issues, none of them rely on an explicit model of risk supporting parametrized reasoning about safety. The majority of the works dealing with safety mainly consider the expected spatial occupancy of human workers to make safer decisions about robot actions. Namely, such works mainly focus on deciding *which* tasks are assigned to the robot taking into account expected spatial requirements to reduce the expected cycle time. A finer-grained model of the risk and collaboration dynamics could instead support more detailed decisions taking into account also *how* to execute robot tasks in order to mitigate potential risks.

The novel contribution of our work thus concerns the design of a detailed risk-aware model of collaborative tasks, based on existing safety standards, and the development of a multi-objective optimization approach to HRC. To the best of our knowledge, this is the first work investigating the use of a risk model extracted from safety standards within a multi-objective task planning framework. More specifically, task and motion planning rely on a timeline-based framework, called PLATINUm [22, 23]. PLATINUm complies with the formal characterization proposed in [24] which takes into account *temporal uncertainty*, and has been successfully applied in real-world manufacturing scenarios [15, 3].

3. Experiments and Evaluation

We realize a task planning system based on a framework already successfully applied in manufacturing scenarios [22, 3]. We implemented a *RiskAssessmentPlanner* with a customized search strategy determining the most promising and safe options to achieve production goals and applying a pareto optimization to balance between safety and efficiency [3]. We consider an experimental scenario inspired by an EU research project (https://www.sharework-project.eu) in which a human and a robot collaborate to build a mosaic [3]. The experiment considers a scenario based on a series of Pick-And-Place operations with a robot and a human collaborating to sort a set of cubes from a common working area into separated heaps, based on the cube's material of different material, i.e., foam, wood, and hot metal cubes, with an increasing intrinsic risk. Each task can be carried out considering three different trajectories and with three increasing speed levels, influencing risk accordingly. Also, we consider human operators with two levels of experience (skilled or not skilled). For each task, we defined a set of precompiled values associated with risk parameters representing an estimation of risk in the considered scenario.

To assess our search strategy, we implement other planners with different heuristics: giving priority to safety (*RiskSearchStrategy*), i.e., aiming to minimize safety and not performance; giving priority to makespan (*MakespanStrategy*), i.e., aiming to minimize makespan and not considering safety; a "classical" depth-first strategy (*PlannerSearchStrategy*). We vary different scenarios varying the amount of shared tasks between humans and robots and a different number of shared cubes. We consider human operators with high experience or with no experience. This allows us to see how the planners react to every combination of parameters. We consider several plan variations, each tested for all strategies and run 5 times per variation, for a total of 160 runs. Tests were performed on a workstation with a Ryzen 3600 CPU and 16 GB RAM.

Our approach enables the planner to make more informed decisions in task allocation and it consistently keeps the risk level low and, whenever possible, significantly enhances efficiency. Though our planner assigns tasks considering the assessed risk and, when feasible, it manages to reduce the risk of collisions. Finally, the planner provides a good trade-off between safety and efficiency reducing the risk of collisions and entailing the highest possible efficiency. The DFS Planner is the fastest as it is only concerned with plan suitability and is not aware of safety or efficiency. Other strategies have similar behavior with RiskPlanner being the one suffering the most from a higher amount of shared cubes. Indeed, a higher shared amount of boxes entails working with a much higher branching factor taking more time to find a solution.

In Figure 1, the scatter plot illustrates how each strategy balances risk and efficiency. Data points are categorized by expertise and shared values. The significant aspect is the right side, indicating RiskAssessmentPlanner's consistent superiority in safety over MakespanPlanner, while being faster than both Planner and RiskPlanner. For less experienced humans, RiskAssessmentPlanner acknowledges the heightened risk, producing safer yet slower plans in response.

4. Discussion and Conclusions

In general, the new risk model allows diverse perspectives in planning systems. Interestingly, in certain experiments, the basic DFS Planner matches the RiskAssessmentPlanner in safety, e.g.,

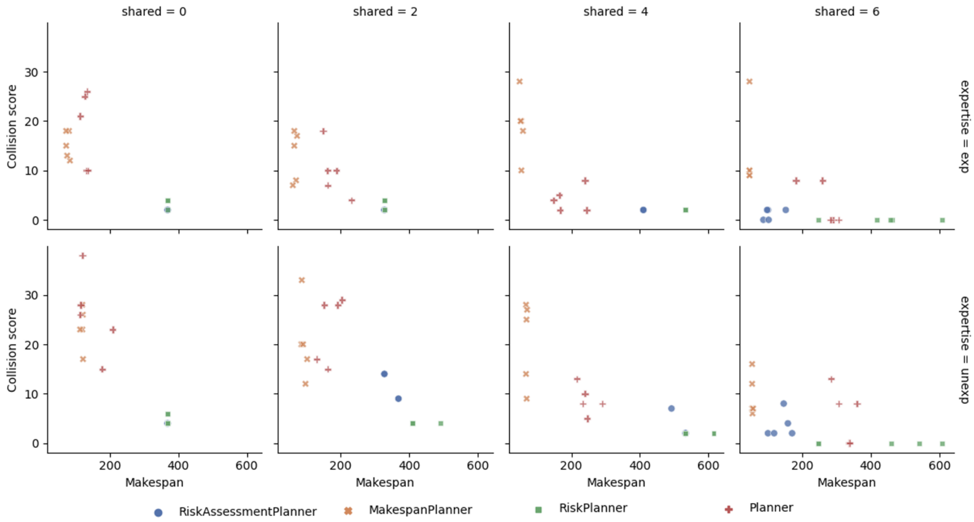

Figure 1: Scatterplot of risk and makespan grouped by expertise and shared tasks

with 6 tasks for experienced workers, and is even safer (though less efficient) for inexperienced workers. This outcome is not entirely unexpected. Although our approach enhances flexibility, optimizing efficiency and safety without compromise remains a challenge, aiming for a trade-off between the two. Indeed, RiskAssessmentPlanner slightly sacrifices safety for better efficiency. Nonetheless, DFS Planner tends to show lower collaboration levels (averaging 5.4 tasks out of 6 assigned to the robot regardless of type). This discrepancy arises because DFS Planner's risk is less impacted by an inexperienced operator who contributes very little (averaging 20-time units compared to the robot's 80).Moreover, despite having a higher risk value, RiskAssessmentPlanner still performs better in terms of collision prevention and task assignment. Therefore, safety levels might appear comparable in plans but there are substantial differences in both average and peak risks. RiskAssessmentPlanner excels in collision handling and task allocation. DFS Planner maintains low risk by mostly assigning tasks to the robot (i.e. limiting collaboration). RiskAssessmentPlanner prioritizes effective task allocation and collision management, even if it means sacrificing efficiency, especially in constrained scenarios.

Integrating diverse risk factors into task sequencing models enables intelligent risk-aware control in human-robot collaboration (HRC). This leverages a state-of-the-art planning framework for risk-aware task sequencing. Our approach showcased efficacy and adaptability across varied simulations, achieving a favorable productivity-safety equilibrium. In future steps, we plan to validate our method in real collaborative setups and incorporate real-time user feedback.

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