A Collaborative Robotics Application for the Assembly of Car Rear Lamps

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A collaborative robotics application for the assembly of car rear lamps

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Abstract. In this work we present the automation of the sticking of small components on car rear lamps, a swift and repetitive operation that is currently performed manually by an operator. The challenging automation of this process includes the delicate pick and place of tiny items in predefined positions on the rear lamps. Pick-and-place trajectories for the robot are planned and a custom end-effector is designed to accomplish the task. Furthermore, a safety approach is implemented to stop the robot in the event of a potential collision with the human operator. Finally, the impact of the cycle time on quantitative metrics for human-robot collaboration, as well as on the mechanical energy of the robot is evaluated. Experimental results on a UR5e manipulator show the feasibility of the operation, while meeting the robot constraints and the cycle time requirements.

Keywords: collaborative robotics, assembly, trajectory planning, speed and separation monitoring, cycle time optimization

1 Introduction

The integration of collaborative robotics in the industry has revolutionized assembly tasks, enhancing efficiency, precision, and safety by seamlessly combining human skills with robotic capabilities. This framework enhances the productivity and flexibility of industrial systems, offering benefits in terms of improved working conditions and ergonomics for operators.

Several examples of robotic systems introduced in collaborative robotics applications to support human workers can be found in the literature, especially in the automotive industry. For instance, in [1] the implementation of a human-high payload robot symbiotic workstation is presented and validated in an automotive case study, namely the assembly of body parts on the vehicle chassis. In [2], a reconfigurable robot work cell aimed at automating low-volume production is proposed. The system is evaluated by implementing five production processes from different manufacturing industries, including the assembly of automotive light housings. Furthermore, the integration of a flexible and reconfigurable work cell performing the assembly of car starters in the automotive industry is described in [3], implementing technologies for the online recognition of human intention and for the real-time learning of robust assembly policies.

In these scenarios, ensuring safety in human-robot collaboration becomes essential. One possible approach to account for safety of the human operator is the implementation of the speed and separation monitoring (SSM) criterion described by the technical specification ISO/TS 15066. For example, in [4] the authors present an approach for the explicit representation of danger zones surrounding the robot to avoid unintended collisions between human and robot in motion. In [5], a method for non-collision between humans and robots while maximizing robot up-time and staying on-path is described. In [6], a computationally efficient planning and control architecture that combines a Rapidly-exploring Random Tree path planner with a trajectory-based Explicit Reference Governor by means of a reference selector is proposed, approximating human skeletons with spheres and cylinders. Moreover, a method based on dynamic safety zones that considers human and robot encapsulated in bounding volumes described as sphere swept lines (SSLs) is presented in [7,8]. More in detail, the size of the safety zones is minimized online, according to the stop time of the robot, and considering the robot dynamics and its torque constraints.

In this work we present the automation of the sticking of small components on car rear lamps, an operation that is currently performed manually by an operator. This research activity includes: (a) the planning of robot trajectories to perform the operation, accounting for the cycle time and the kinematic constraints of the robot and the workspace; (b) the investigation of pick-and-place operations, including the design of a custom gripper; (c) the implementation of a safety approach to stop the robot in case of potential collision with the human operator; and (d) the evaluation of the impact of the cycle time on quantitative metrics for human-robot collaboration, as well as on the mechanical energy of the robot. Experimental results on a UR5e manipulator show the feasibility of the operation, while meeting the robot constraints and the cycle time requirements.

The paper is organized as follows: Sect. 2 illustrates the problem addressed in this paper, whereas the proposed approach for the automation of the process is described in Sect. 3. The experimental results are reported in Sect. 4. Finally, Sect. 5 concludes the work.

2 Assembly of car rear lamps

The problem addressed in this paper is the automation of the procedure for the sticking of small components on car rear lamps. Specifically, we consider a case study with eight small adhesive items that need to be placed at specific locations on the back of a pair of rear lamps. Currently, this operation is carried

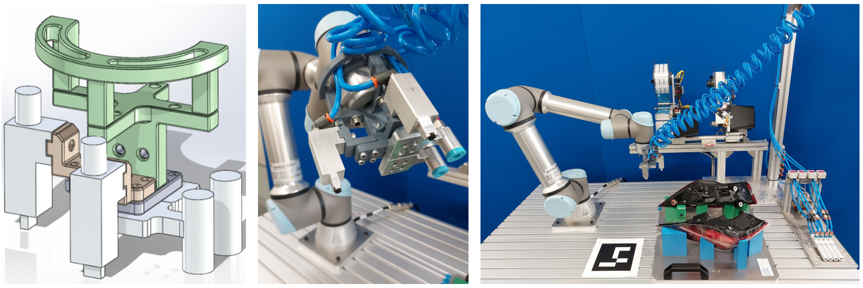
(a) (b) (c)

Fig. 1: End-effector design (a) and prototype (b); robot workstation (c).

out manually by an operator who takes the components from a dispenser and positions them at the desired points. The workspace accommodates two rear lamps that are processed within the same cycle. Each cycle involves placing four pieces per headlight (two round in Goretex and two rectangular in film), for a total of eight items to be positioned per cycle. The desired cycle time of this case study is approximately 45 seconds.

The goal of this work is to automate this procedure using an industrial robot, thereby reducing or eliminating the need for human operator intervention. More in detail, this research activity includes:

- The planning of the trajectories for the robot that will perform the operation. These trajectories must take into account the cycle time and the kinematic constraints of the robot and the workspace.
- The investigation of pick (items retrieval from the dispenser) and place (items positioning on the headlight) operations, considering the critical aspects related to gripping the components and adhering them to the rear lamps.
- The implementation of a safety approach to stop the robot in the event of potential collision with the human operator.
- The evaluation of the impact of the cycle time on quantitative metrics for human-robot collaboration, as well as on the mechanical energy of the robot.

3 Automation of the process with a UR5e robot

The first part of the research activity focuses on the design of the workstation and the gripping system for the components to be attached to the rear lamps. For this application, the UR5e manipulator by Universal Robots is used (Fig. 1).

To design the workstation, a preliminary pick-and-place program is developed in which all the positions of the way points are parameterized relative to the robot base reference frame. This approach allows for the quick adjustment of the relative positions among rear lamps, dispenser, and robot base, ensuring smooth robot movements without encountering singularities or joint limits.

The end-effector of the robot is designed so as to be capable of picking and placing the items using a vacuum system connected to an air compressor, by considering the potential collisions with the dispensers and the housing of the rear lamps (Fig. 1a). Four custom suction cups are connected to the robot flange by means of ad-hoc supports. The support parts (Fig. 1b) are built in PLA using an Ultimaker Pro Bundle 3D printer. Using the suction cups, the robot can pick the items from the dispensers and place them of the rear lamps with simple rotations of 90° of its sixth joint. Furthermore, the end-effector is realized so as to avoid excessive vibrations of the suckers during the motion of the robot, prevent air pipes from twisting, and minimize the printed material.

Pick-and-place trajectories are studied to ensure the correct gripping and positioning of the four stickers within a predefined cycle time. Additionally, the kinematic constraints of the robot are taken into account, as well as potential unwanted collisions with the worktable, rear lamps, and the stickers dispensers.

The gripping of the round stickers and the placement of all four stickers (round and rectangular) are managed using the force control, which enables the robot to search for and identify the position of a rigid surface by moving at low speed and stopping upon contact. During the task execution, the vacuum pressures are monitored to interrupt the operation if a component has not been correctly retrieved from the dispenser. Furthermore, the operator can choose whether to perform the sticking task on one or both rear lamps.

To guarantee safety of the human operator in case of potential collision with the robot, the approach based on the optimal scaling of dynamic safety zones described in [7,8] is implemented. The strategy is based on online safety checks between bounding volumes enclosing robot and human to identify possible collisions. The safety zones enclosing the manipulator are defined by minimizing the potential stop time and considering the robot dynamics, its kinematics and torque constraints, and the directed speed of the robot parts with respect to the human. The approach follows the SSM criterion of the ISO/TS 15066, that provides a protective separation distance to be maintained when the robot is in motion. Otherwise, a stop trajectory is triggered. The optimization problem for the minimization of the stop time is subjected to position, velocity, acceleration, jerk, torque and torque rate constraints (see [7,8] for the complete formulation).

To verify the torque constraints during the stop time, the dynamic model of the robot identified in [9] is adopted. In this work, the dynamic model parameters are considered to be known. However, in case of imperfect knowledge of the robot dynamics, an approach based on interval arithmetic can be adopted to meet joint torques limits [10]. The optimization problem is implemented in Python with the open source tool CasADi [11], using the recursive Newton-Euler inverse dynamics of the robot in symbolic form.

The position of the human is tracked online with a Intel RealSense D345 camera, using CUDA and Open Pose on an NVIDIA Xavier computer. Once the coordinates of the human body parts are detected, the minimum distance between robot and human is efficiently computed by analyzing line segments defining the bounding volumes of both, and a robot stop is triggered if needed.

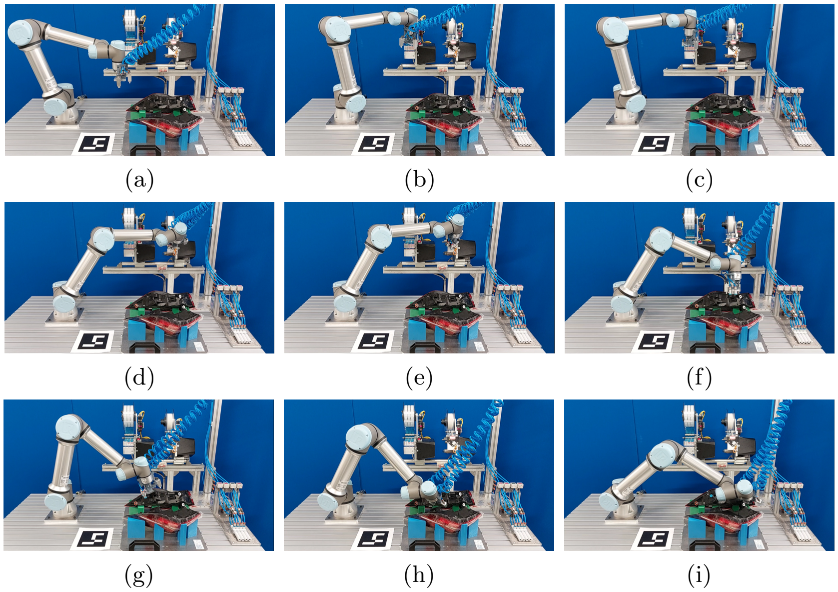
(a) (b) (c) (d) (e) (f) (g) (h) (i)

Fig. 2: Exemplary frames of the process: (a) homing position; (b) pick first round sticker; (c) pick second round sticker; (d) pick first rectangular sticker; (e) pick second rectangular sticker; (f) place first rectangular sticker; (g) place second rectangular sticker; (h) place first round sticker; (i) place second round sticker.

4 Experimental results

Figure 2 reports exemplary frames of the sticking process: the robot is able to complete the whole process of picking and placing the stickers in approximately 45 seconds, while meeting its kinematics and dynamics constraints. Fig. 3a shows an example of a human intrusion in the workstation that needs to induce a safety stop of the robot. Furthermore, Fig. 3b and 3c show a representation of human and robot enclosed in bounding volumes, keeping a safety clearance, and during a robot stop, respectively.

To evaluate the impact of the cycle time on quantitative metrics for human-robot collaboration, the 3D joint coordinates of the skeleton of the human operator during an intrusion in the robot workspace are recorded. These coordinates are then used in playback in multiple tests, during which the cycle time of the robot is progressively increased. For each value of the cycle time, experimental tests are performed repeating the process ten times, while the recorded human skeleton induces safety stops of the robot. The human skeleton is played back in loop until the robot has completed its task (i.e., the assembly of ten pairs of rear lamps). Furthermore, the tests are repeated four times, by increasing the speed of the recorded human skeleton (e.g., ×1 for Test n.1, ×2 for Test n.2, ×3 for Test n.3, and ×4 for Test n.4). In Fig. 4 an exemplary trajectory for one cycle

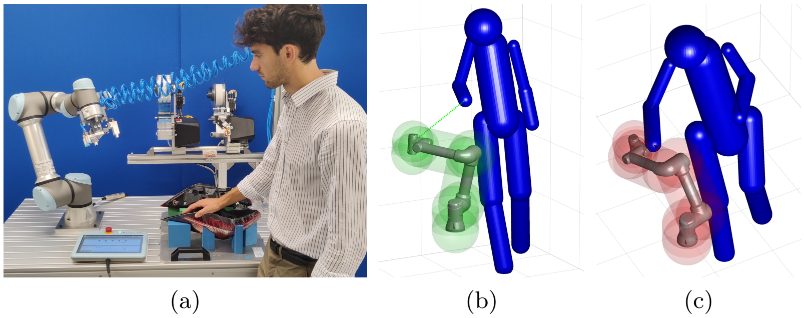

Fig. 3: Human intrusion in the robot workspace (a); human and robot enclosed in bounding volumes keeping safety clearance (b), and during a robot stop (c).

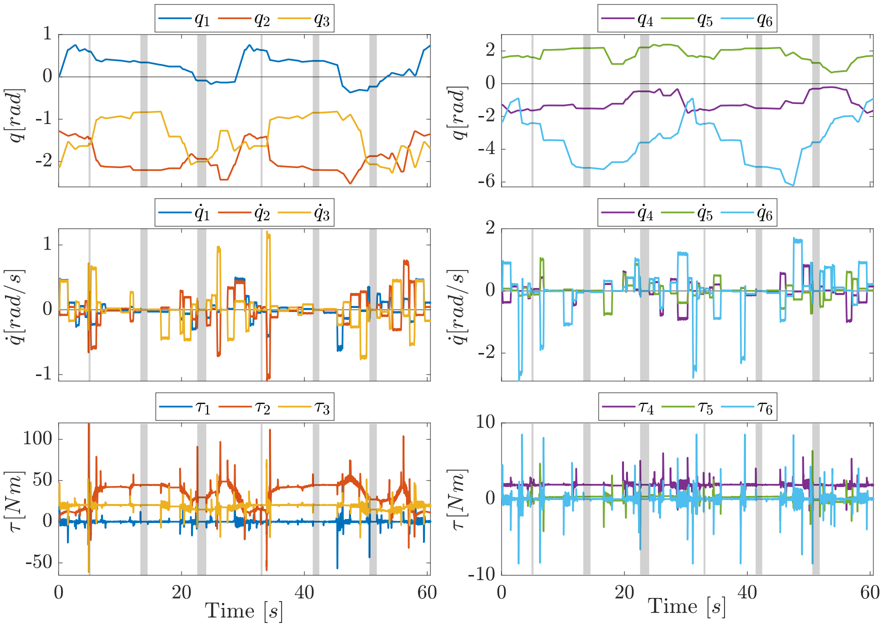

Fig. 4: Exemplary joint positions, velocities, and torques over time for one cycle.

with a duration of approximately 60 seconds (comprising the processing of two rear lamps) is shown, including joint positions, velocities and torques over time. Grey shaded areas indicate safety stops of the robot.

We consider the following metrics to evaluate the impact of the cycle time on the human-robot collaboration quality, and on the robot energy consumption:

- Total task time (T-TIME): the total time required to complete ten assemblies, including safety stops of the robot;

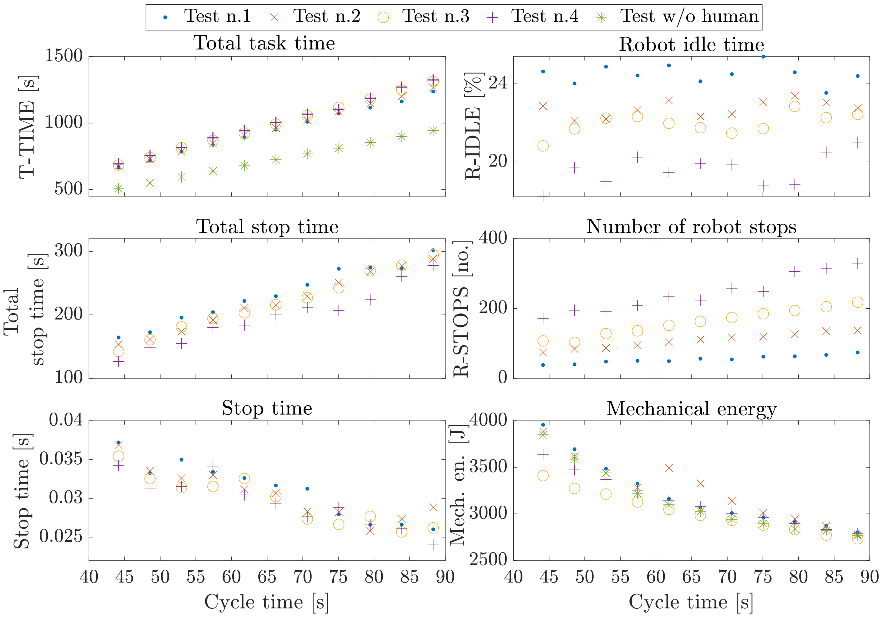

Fig. 5: Experimental results for different values of the cycle time (ten repeated cycles are performed for each value).

- Robot idle time (R-IDLE): the percentage of the total task time the robot is not moving during the execution of the task;
- Total stop time: the total time the robot is not moving;
- Number of robot stops (R-STOPS);
- Stop time: the root-mean-square value of the stop times;
- Mechanical energy: computed as the integral of the mechanical power over time. It measures the energy consumed by the robot during the task, which is an essential index to improve efficiency and sustainability [9,12].

The top-left graph in Fig. 5 show that the total task time increases with the cycle time. Furthermore, in that plot the green markers indicate the nominal duration of the task if the human intrusion is not considered. No appreciable differences in the T-TIME can be seen by varying the human speed. The R-IDLE (top-right plot in Fig. 5) is less then 26% for all the values of cycle time. By increasing the human speed, R-IDLE decreases. The total stop time and the number of robot stops increase with the cycle time (central plots in Fig. 5). The number of robot stops is higher if the skeleton speed is higher. The robot stop time (bottom-left plot in Fig. 5) has a decreasing trend with the cycle time, since the robot generally travels at lower speed. The stop time is always below 0.038 s. Finally, the mechanical energy of the robot generally decreases by increasing the cycle time. This is also mainly due to the lower robot speed during the execution of the tests. No appreciable difference in the energy consumption of the robot can be seen due to the intrusion of the human in the robot workspace.

5 Conclusion

In this work we presented the automation of the sticking of tiny items on car rear lamps. Pick-and-place trajectories for the robot have been planned and a custom end-effector has been designed. Furthermore, a safety approach has been implemented to stop the robot in case of potential collision with the human operator. Finally, the impact of the cycle time on human-robot collaboration quality, and on the mechanical energy of the robot has been assessed. Experimental results on a UR5e manipulator have shown the feasibility of the operation, while meeting the robot constraints and the cycle time requirements.

Acknowledgments

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