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SECTION 5.
AUTOMATION AND APPLIANCES MAKING

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METHODS FOR OPTIMIZING THE BUILDING OF COLLABORATIVE ROBOT ROUTES IN A DYNAMIC ENVIRONMENT

Modern collaborative robots (cobots), which work alongside humans in a shared workspace, must plan trajectories that simultaneously meet the requirements of safety, smooth motion, timely responsiveness to dynamic obstacles (people, other robots, moving objects), energy efficiency, and task accuracy [1,2]. The dynamic environment imposes additional constraints on the planner: incomplete information about future obstacle trajectories, uncertainty in sensor measurements, rigid kinematic/dynamic constraints of the robot, and the need for fast real-time response [3-5]. Because of this, trajectory optimization in a collaborative context usually requires a combination of: predictive models of human/obstacle behavior, rapid local corrections, and global optimality criteria — which is why the comparison of methods should focus not only on "trajectory quality" but also on computational costs, safety guarantees, and integration with human behavior prediction [6-9].

Below is an analysis of existing optimization methods that can be used to build a route for a collaborative robot in a dynamic environment:

- sampling-based planners (sampling-based: RRT, RRT*, PRM, and their modifications). Advantages: work well in high-dimensional configuration spaces, quickly find feasible paths in irregular geometry; there are asymptotic guarantees of optimality in the RRT* and PRM* versions. Disadvantages for dynamic environments: basic versions do not take into account the time component (i.e., moving obstacles) without extensions; if smoothness/dynamics are required, further trajectory optimization is often necessary; sensitive to the frequency of obstacle map updates. Practical considerations: used as a fast global search (to find a homotopy or rough trajectory), followed by local optimization;

- trajectory optimization methods (CHOMP, TrajOpt, STOMP, etc.). Advantages: directly minimize quality functionals (energy, smoothness, distance to obstacles), easily introduce kinematic/dynamic constraints, produce smooth trajectories, convenient for high-dimensional manipulators. Disadvantages: require good initialization (to avoid local minima), can be computationally expensive, basic variants are non-dynamic (but there are extensions for dynamic obstacles). Practical notes: often combined with sampling - sampling gives the initial path, the optimizer smooths and adjusts to the constraints;

- Model Predictive Control (MPC / NMPC). Advantages: naturally takes into account time constraints, robot dynamics, and predicted obstacle movements in the form of a prediction window; allows you to set constraints and objective functions in "online" mode, well suited for real time with fast optimizers. Disadvantages: requires an accurate model (or its adaptive update), computational costs can be high for complex nonlinear models or long prediction horizons; sensitivity to errors in predicting human movement. Practical considerations: MPC is particularly useful as a local controller/planner working on a pre-found global trajectory or as a standalone online planner with powerful hardware and optimizers such as PANOC/HPIPM;

- reactive and behavioral methods (potential fields, dynamic window, velocity obstacles, ORCA). Advantages: fast response, ease of implementation, natural integration into resource-constrained systems; useful for avoiding immediate collisions. Disadvantages: no guarantee of global optimality, susceptibility to local minima, difficult to guarantee smoothness and comfort of movement when operating in a human environment. Practical notes: effective as a "quick layer" of collision avoidance in the planning hierarchy (the reactive layer increases safety between global plan updates). (see reviews on avoidance);

- learning approaches: reinforcement learning (RL), imitation learning, hybrid learning+planner. Advantages: capable of learning complex behavior policies in unpredictable conditions, adapting to people's styles in collaboration, can reduce computation during execution (policy inference is faster than optimization "on the fly"). Disadvantages: require large amounts of data/simulations, fewer formal safety guarantees; difficult to certify in industry. Practical considerations: often used in hybrid architectures - trained policy provides initialization/quick response; optimization methods provide guarantees and accuracy.

- hybrid/multi-level approaches. The most practically viable solutions combine global sampling or a trained global planner + local MPC/optimization + a reactive layer for instant collision avoidance. This division allows the strengths of each approach to be leveraged: global optimality/topology awareness, local dynamic coordination, and guaranteed safety in the face of unforeseen events. Recent studies show that parallel optimization of multiple homotopies or generation of sets of evacuation trajectories significantly increases resilience to unforeseen events.

Conclusions. Research into methods for optimizing the construction of collaborative robot routes in a dynamic environment has shown that there is no universal approach, and that the effectiveness of solutions depends on a combination of global and local strategies. The analysis demonstrated that sampling-based algorithms, such as RRT* or PRM*, are well suited for quickly finding feasible trajectories in complex spaces but require additional smoothing and optimization. Optimization-based methods, such as CHOMP and TrajOpt, ensure smoothness and take kinematic constraints into account, but have high computational complexity and sensitivity to initialization. Model predictive control (MPC) has proven to be an effective approach for dynamic scenarios, as it takes into account the time component and allows for the integration of human movement predictions, but requires high computational resources and an accurate system model. Learning methods and hybrid architectures combine the strengths of classical algorithms with adaptability, which is especially important for working in conditions of uncertainty. The results of the study confirm that the optimal solution involves a multi-level planning structure, where a global planner, local optimizer, and reactive layer work together to ensure safety, smooth traffic flow, and real-time compliance. Thus, to achieve high efficiency and reliability in collaborative systems, it is advisable to combine several optimization methods, taking into account the specifics of the environment and the limitations of the hardware platform.

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