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Robust multi-robot coordination in pick-and-place tasks based on part-dispatching rules

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HIGHLIGHTS

- Propose combination of part-dispatching rules to coordinate multi-robot system.
- Pattern variation in a pick-and-place task is taken into account.
- Achieve an appropriate part flow and combination of part-dispatching rules.
- Integrate a greedy randomized adaptive search procedure with a Monte Carlo strategy.

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ABSTRACT

This paper addresses the problem of realizing multi-robot coordination that is robust against pattern variation in a pick-and-place task. To improve productivity and reduce the number of parts remaining on the conveyor, a robust and appropriate part flow and multi-robot coordinate strategy are needed. We therefore propose combining part-dispatching rules to coordinate robots, by integrating a greedy randomized adaptive search procedure (GRASP) and a Monte Carlo strategy (MCS). GRASP is used to search for the appropriate combination of part-dispatching rules, and MCS is used to estimate the minimum-maximal part flow for one combination of part-dispatching rules. The part-dispatching rule of first-in–first-out is used to control the final robot in the multi-robot system to pick up parts left by other robots, and the part-dispatching rule of shortest processing time is used to make the other robots pick up as many parts as possible. By comparing it with non-cooperative game theory, we verify that the appropriate combination of part-dispatching rules is effective in improving the productivity of a multi-robot system. By comparing it with a genetic algorithm, we also verify that MCS is effective in estimating minimum-maximal part flow. The task-completion success rate derived via the proposed method reached 99.4% for 10,000 patterns.

1. Introduction

1.1. Background

Industrial robots and conveyors have been widely applied in manufacturing to create product lines. Such a robot system can complete diverse industrial tasks, particularly, pick-and-place tasks. Compared with robot systems with a single robot, a system with multiple robots may be preferable because it may improve productivity [1–3]. In this paper, we investigated a real application of multi-robot system in pick-and-place tasks [4,5]. Multiple robots, a moving conveyor and multiple packaging boxes make up a multi-robot system, as shown in Fig. 1. The parts are fed onto one end of the conveyor by a part feed device and move through the robot workspace. When importing robots to a production line, the part feed device normally cannot be modified. Therefore, it is reasonable to consider that the parts are fed onto the conveyor follow some probability distribution in a real application [6]. We define a pattern as the process of feeding parts onto the conveyor following a given distribution with a random seed. Each robot picks up parts moving through its workspace and places them in the

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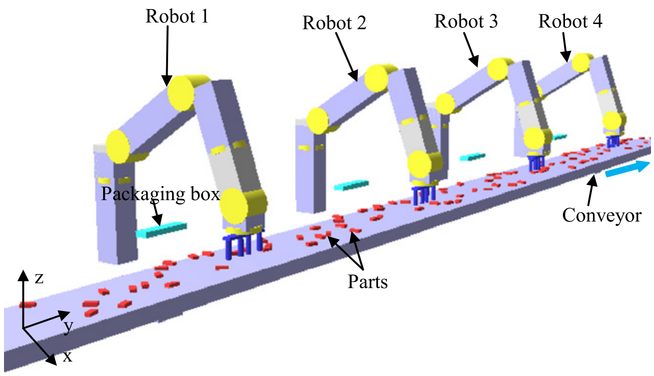

Fig. 1. Multi-robot system for pick-and-place tasks.

packaging box. The parts remaining on the conveyor are collected by a collecting box.

For a multi-robot system performing pick-and-place tasks, a fundamental challenge is how to dispatch parts to the appropriate robot so that each robot picks up as many parts moving through its workspace as possible. Part-dispatching rules (e.g., first-in–first-out (FIFO) and shortest processing time (SPT)) have been used to control a single robot because of the rules' intuitive appeal, low control computation time, and ease of implementation [7]. Different part-dispatching rules can be used for the different robots in a multi-robot system (e.g., one possible combination of part-dispatching rules for a system with four robots is "FIFO, FIFO, SPT, SPT"). High part flow (i.e., number of parts fed per time unit) can improve the productivity of a multi-robot system but may mean that many parts are left on the conveyor, therefore requiring many collecting boxes to collect these parts. If the remaining parts are returned to the feeding conveyor through a return conveyor instead of having a collection box at the end of the feeding conveyor, additional device cost is required. Furthermore, the remaining parts may be overlapped by the new fed parts when the remaining parts are returned to the feeding conveyor. Conversely, low part flow reduces productivity. Therefore, for a multi-robot system performing pick-and-place tasks, it is important to use an appropriate part flow and combination of part-dispatching rules. However, the pattern variation (i.e., the process of feeding parts following a given distribution with different random seeds) affects the part flow and combination of part-dispatching rules. To improve productivity and reduce the number of remaining parts, it is therefore necessary to use an appropriate part flow and combination of part-dispatching rules that are robust against pattern variation (i.e., multi-robot coordination that is robust against pattern variation). Because there are an infinite number of patterns in a real application of a pick-and-place task, it is difficult to control the pattern to obtain the optimal part flow and combination of part-dispatching rules. In this paper, we define a minimum-maximal part flow as the maximal part flow for one combination of part-dispatching rules under the worst pattern, define a worst pattern as a pattern that produces the minimum-maximal part flow, and define a robust part flow and combination of part-dispatching rules as one that enables the multi-robot system to complete a task against pattern variation [8–10]. The part flow and combination of part-dispatching rules will be robust against other patterns if the minimum-maximal part flow and combination of part-dispatching rules under a given pattern can be obtained [8]. This requires mini–max optimization of the system against pattern variation.

1.2. Related works

Although most researches have focused on single-robot conveyor systems [7,11,12], multi-robot systems are receiving increasing attention because of their high productivity. In previous studies, most researches focused on the coordination of multiple robots. Some researches aimed to develop a multi-robot coordination architecture [13–17]. In [13], an architecture called ALLIANCE was proposed to allow each robot to possess a variety of high-level functions that it can perform during a mission. The appropriate actions for a robot can be individually selected based on the robot's own internal states, current environmental conditions, activities of other robots, and task requirements. In [14], a framework and software architecture were proposed to coordinate multiple robots in an unstructured and unknown environment. This architecture was based on the assumption that each robot had a finite set of behaviors and the programming language was used to formally specify a set of conditions. An implicit communication behavior based architecture was proposed in [15], in which a source of implicit information about the robots' intention to be involved in collective actions should be provided by the configuration of the environment. A sense–model–plan–act architecture was proposed in [16], in which functional, control, and planner levels were used to manage robot resources and carry out complex operations. In [17], a flexible architecture that provides asynchronous operation in control modules at high level and synchronous control at low level was proposed to coordinate multiple robots to improve the throughput.

Some other researches aimed to develop multi-robot coordination strategies or algorithms [5,18–22]. An approach was developed to coordinate robots for pick-and-place tasks on a conveyor based on non-cooperative game theory in [5]. The action of each robot was determined according to the local observations of the conveyor and the actions of its neighbors. In [18], a model of a robotic palletizing process involving two robots with overlapping workspace was proposed based on queuing theory. Such model is difficult to apply in the multi-robot system with non-overlapping workspace, because the queuing model for the multi-robot system with non-overlapping workspace is difficult to be built. In [19], a state-action map with reinforcement learning was proposed to dispatch parts to two robots. The method based on the state-action map was compared with two simple part-dispatching rules. In [20], a practical approach and explanatory Gantt plots were used to minimize the cycle time of manufacturing lines with multiple dual-gripper robots. In [5,18–20], the part flow on the conveyor was predefined. Some algorithms were proposed to solve the multi-robot coordination problem known as distributed constraint optimization problems [21,22], in which each of the multiple robots controls a single variable and the robots aim to maximize a global objective function. However, it is difficult to form a global consensus for all robots in many scenarios and each robot has to consider all the associated robots' payoffs when it makes a decision.

By using the existing multi-robot coordination architecture, strategy, or algorithm to coordinate the actions of robots, it is difficult to tune the design parameters to obtain the best performance due to the complexity of architecture, strategy, or algorithm. When the number of robots in the system is large, the communication load between robots is much and a large memory is required. In contrast, part-dispatching rule is intuitive and no communication between robots is required when we use the part-dispatching rules to control the action of robot. Although many researchers have focused on the multi-robot coordination, none of them took into account the combination of part-dispatching rules to coordinate multiple robots and the robust part flow and combination of part-dispatching rules against pattern variation in pick-and-place tasks.

1.3. Purpose of this study

The aim of this study was to achieve an appropriate part flow and combination of part-dispatching rules for a multi-robot system that are robust against pattern variation in pick-and-place tasks.