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Asynchronous cooperation requirement planning with reconfigurable end-effectors

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ABSTRACT

Automation processes in an unstructured environment are challenged by changing peripheral requirements. Reducing the cost of peripherals is a major concern for system designers. Addition of extra flexibility to the existing equipment to handle a larger range of tasks is a desirable solution, which can be offered by reconfigurable end-effectors (REEs). A REE system has an adjustable structure to facilitate the adaptation of the end-effectors to various objects, so it is an intermediate solution between flexible and dedicated end-effectors. To balance the trade-off between the production quality and the reconfigurability becomes the main difficulty in the design and control of REE. In this work, the models of configuration network and order of reconfigurability are introduced to provide theoretical analysis of the reconfigurability in REE. Based on the analytical models, the asynchronous cooperation requirement planning (ACRP) framework is established to facilitate the effective design and control of REE. ACRP provides a dynamic solution extended from the planning facet of collaborative control theory (CCT) for designing (offline) and controlling (online) multi-agent collaborations. ACRP determines how flexible an automation system should be considering the cost of reconfigurations and the quality of production. The framework is illustrated with a case study of vegetable harvesting by multi-arm automated systems. In harvesting processes, the grasp quality is one of the most important factors for production quality. Simulation experiments in the current article show that both new and previous CCT methods increase average grasp quality of harvesting by 14% compared to harvesting without CCT. Furthermore, the new framework, ACRP, outperforms the previous CCT method, by a 7% improvement of the total harvest yield.

1. Introduction

Reconfigurable manufacturing systems (RMSs) are considered to be an intermediate category between dedicated manufacturing systems (DMSs) and flexible manufacturing systems (FMSs) [1, 2]. RMSs have adjustable structures to adapt to the production needs of a family of products. These adjustments include changes to machine functionality and process scalability. RMS design conventions also call for modularity, that is, using common building blocks and interfaces. In production, the RMS should be capable of operating at different locations performing different tasks [2]. Because RMSs are not as flexible as FMS, they are also not as expensive. RMSs have been designed for various application fields, including machining, inspection, and assembly.

A major cost of constructing an automated system is the cost of dedicated peripheral components, such as robot end-effectors, fixtures, feeders, sensors, etcetera. In contrast, manipulators are considered to be flexible and can usually be used in several processes. Hence, the end-effector design has been specifically targeted in this article due to its important role in facilitating job execution. End-effectors can be divided into two categories: tools and grippers. Tools facilitate the work on stationary objects, and grippers facilitate object manipulation. The most common grippers are mechanical grippers with two or more actuated fingers. Task-specific grippers include vacuum, magnetized and adhesive devices [3].

As with manufacturing systems, in between flexible and dedicated end-effectors there exists an intermediate category of reconfigurable end-effectors (REEs). REEs include both interchangeable tools and grippers with interchangeable fingers [4]. To change the tools and fingers automatically, a common connection mechanism is required between the two connecting parts [5]. Automatic tool changers have been developed since 1970s [6]. They are often criticized for the long time required to change tools. The increased cycle-time of changing a REE during a process causes production delay. More rapid changes can be achieved through reprogramming grasp gestures of flexible grippers. In [7], researchers designed a

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Abbreviation and Nomenclature

ACRP	Asynchronous Cooperation Requirement Planning
CCT	Collaborative Control Theory
CRP	Cooperation Requirement Planning
DMS	Dedicated Manufacturing System
DOP	Degree of Parallelism
FMS	Flexible Manufacturing System
GQO	Grasp Quality Optimization
OOR	Order of Reconfigurability
RMS	Reconfigurable Manufacturing System
D_i	Reconfiguration cost in configuration network layer i
G	Minimum grasp cost
g_{ijt}	One-time grasp cost at arm i uses end-effector configuration j to accomplish job t
$G_i(d)$	Grasp cost of end-effector configuration i as a function of the size of grasped object
J	Total design cost
M	Total number of configurations
M_i	Number of reconfigurable parts in layer i
$\mathbb{M}_i$	Maximum number of reconfigurable parts in layer i
N	Number of arms
$\mathbb{N}$	Maximum number of arms
$p(d)$	Grasped object distribution as a function of object's physical dimensions (d)
q	Average grasp quality
R	Estimated reconfiguration cost
r_{ij}	One-time reconfiguration cost for arm i to use end-effector configuration j
v	Harvesting platform forward velocity
X_{ijt}	Decision variable on whether arm i uses end-effector configuration j to accomplish job t
Y	Total yield
z	Total control cost
λ	Rate of vegetable density in field
μ	Average service rate of harvesting processes
ρ	Production cost
Φ	Number of jobs optimized in Eq. (7)

reconfigurable gripper which precisely grasped typical automotive body panels with different geometries. There are various on-going attempts at engineering flexible grippers capable of dexterous grasping [8]. Although much progress has been made both in mechanical design and in gripper control algorithms, current flexible grippers are far from meeting industrial grade demands for product quality and system robustness. From a system integrator's point of view, the major problem of building REEs is to determine how reconfigurable the system should be. The system's optimal reconfigurability should show optimal production quality as well as reduced cost and time consumption in the reconfiguration operations. It is a fundamental question lining up with design of assembly: How to trade-off between adaptation flexibility and application flexibility when the total cost is limited [9]. To achieve application flexibility, more specific gripper configurations should be integrated into the production system, because dedicated grippers reach relatively higher quality and robust grasps. However, the cost of reconfiguration (on cycle-time, energy, etc.) is increased due to complex reconfiguration mechanisms, which reduce the adaptation flexibility. Currently, the solution to this problem has not been well researched.

Production systems become more complex, and the number of components and the interactions among them increase. Optimizing system design and control become more challenging. Collaborative Control Theory (CCT) is a framework of principles for the design and control of complex systems with multiple agents in networked organizations and facilities [10]. Collaboration in such highly interconnected environments becomes a necessity for the achievement of reliable, timely, and cost-effective goals. Collaboration implies the sharing of information, resources, and tasks. CCT framework offers a promising direction for optimizing design and control of automation cells with REEs. Cooperation Requirement Planning (CRP) is the first (out of six) design principle of CCT [11, 12]. CRP enables efficient design and control of automation based on tasks and available resources. Collaborative e-Work Parallelism is another principle of CCT for deriving the optimal Degree of Parallelism (DOP) of different components performing different tasks in a system [10, 13]. As many components in the automated system are working in parallel, the planning of executions and configurations becomes even more challenging. Asynchronous Cooperation Requirement Planning (ACRP) framework is thus introduced in this research. The objective is to accomplish the design and control of automation systems with REE in a stochastic task environment.

The proposed methodology - ACRP is for the design of REE in automated systems and for optimizing their processes. It is commonly accepted that less constrained environments require higher flexibility. We chose to examine the ACRP in a harvesting case study in which the environment is unstructured and the grasp quality is highly demanding [14].

In food industry, the automation of fruit and vegetable harvesting, for example, by fruit-picking systems, is under research and development to enhance productivity (a recent review can be found in [15]). These automation solutions are designed to perform harvesting processes selectively, that is, picking only ripe fruits and vegetables. There has been much research on vegetable selective harvesting systems but few are commercialized so far [16, 17]. The main limitations are the diversity of plant properties, slow operations and seasonal effects. In order to overcome these limitations, careful planning and control of the harvest processes is required. Since the harvesting process of crops is usually conducted in a relatively short period of a year, a dedicated system that only handles one type of fruit or vegetable is not economical. Therefore, other operations are integrated into harvesting systems, such as pruning, bagging, and spraying which are necessary during harvesting. Another option is to make the automated system reconfigurable to harvest different items in different seasons throughout the year, so the system is reused on demand. Fruits and vegetables have different shapes, sizes, and require maximum adherence with minimal pressure when being detached from stems [14]. Thus, integrating REE into robotic harvesting systems is beneficial. As multiple arms can be implemented to work in parallel, asynchronous planning is required for an automated harvesting platform, including the coordination with the platform's mobility.

The main contributions of this article are: (1) establishing the ACRP framework for the design and control of REE in an automation system; (2) designing the objective functions that capture the trade-off between cost of reconfigurations and quality of production; and (3) applying ACRP in a robotic harvesting system with multiple arms and REE.

The remainder of this article is structured as follows. Section 2 shows the ACRP framework and the assumptions used by this research. The design of the reconfigurability, including Order of Reconfigurability and Configuration Network, is explained in Section 3. The control of reconfiguration of REE during a process is illustrated in Section 4. Section 5 describes the experiments of