Design and simulation based validation of the control architecture of a stacker crane based on an innovative wire-driven robot

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ABSTRACT

Automated Storage/Retrieval Systems (AS/RS) have an important role in the improvement of the performance of automated manufacturing systems, warehouses and distribution centers. Existing AS/R systems are usually based on Cartesian Storage/Retrieval Manipulators (SRM). Such systems have reached their maximum performance due to the limitations of their underlying mechanical design and associated control architecture. Going beyond the limits of existing systems requires structural innovation and breakthrough solutions to enhance their design and performance. In this study, we introduce the design and simulation based evaluation of a stacker crane based on an innovative wire-driven SRM. We describe the basic components and provide an overview of the mechanical design of the system. We design the high-level control architecture that allows handling mini-load operations. We develop the equations that determine the single and dual command cycle times for the wire-driven SRM in case of random and class-based storage policies. We validate the suggested control architecture using a simulation software specifically developed for this purpose. We benchmark the wire-driven SRM against an equivalent Cartesian SRM. Results show that the new wire-driven SRM design and control architecture are more competitive than Cartesian SRM in terms of travel cycle times, and more suitable for buildings growing in height.

1. Introduction

Automated Storage and Retrieval Systems (AS/RS) are computer-controlled material handling systems that are used to automatically place loads into and withdraw them from defined storage locations [1]. An AS/RS implements a defined degree of automation to ensure speed and precision in performing storage and retrieval operations [2]. AS/RS were first introduced in the 1950s to eliminate (or at least reduce) drawbacks of manual material handling [1,3]. Nowadays, AS/RSs are used in many manufacturing industries, distribution centers and warehouses. They contribute to save time and cost by limiting both damage to products and non-value added labor related manipulations [4]. They have many advantages over traditional (usually manual) storage technologies, such as improving system efficiency and space utilization, increasing reliability, reducing error rates and costs (e.g. due to labor, damage, or loss by theft) [1]. AS/RS contribute to facing continuous change in a company’s internal and external environments, due to several factors, including the challenges of meeting the fluctuating production volumes, reducing energy consumption, improving inventory management, tracking and traceability, etc.

1.1. Crane based mini-load AS/RS

Since the 1950’s, there have been many advancements in AS/RS technology. Many types of AS/R systems exist, which differ according to various options classified in [5]. Crane based mini-load AS/RS are of particular interest to us in this article. Such systems are designed to handle unit loads that generally correspond to bins, and typically consist of the following main components illustrated in Fig. 1:

- **Racks** are typically metal structures with locations that can accommodate loads (e.g., pallets, tote boxes);
- **Cranes** are the fully automated storage and retrieval machines/
Fig. 1. Structure of crane based AS/RS [1].

manipulators (SRM) that can autonomously move, pick up and drop off loads;

- Aisles are formed by the empty spaces between the racks, where the cranes can move;
- An input/output point or station (I/O-point) is a location where retrieved loads are dropped off, and where incoming loads are picked up for storage.
- Pick positions (if any) are places where people are working to remove individual items from a retrieved load before the load is sent back into the system.
- Management and control system, which is a computer software used to manage space, track inventory and monitor SRM movements.

Much research has been devoted to designing and controlling crane based AS/R systems in order to improve precision and speed in performing storage and retrieval operations [2,5,6]. Many references discussed issues related to the design and operation of AS/R systems in order to optimize their performance [5,7–9]. These issues include concerns about sizing the AS/R, i.e. how to determine settings and trade-offs related to the number of racks, their length and width, the number and dimensions of storage compartments, their capacity (single or double deep), the number of loads transported by the crane (single or dual shuttle), and the number of cranes. These issues also include concerns about management strategies, such as storage assignment policies, batching, dwell point location (i.e. location of the crane when it is idle), and sequencing of storage and retrieval requests. However, although questioning the crane design and motorization would allow significant improvement of performance, very few works considered the limitations due to the mechatronic design and actuation of the crane itself.

1.2. Limitations of Cartesian S/R machines

Existing mini-load AS/Rs are usually based on a Cartesian robot that has three separate mechanical drives:

- A vertical drive, which raises and lowers the mini load;
- A horizontal drive, which moves the mini load back-and-forth along the aisle;
- A shuttle drive, which transfers the mini load between the S/R machine carriage and both sides of the aisle.

These drives are often operated separately to transfer a load between any two points (for example from an I/O station to a storage location, or between storage and retrieval locations). The mast of the S/R machine moves horizontally along the aisle, while a shuttle moves vertically up and down the mast. Such separate and simultaneous drive operation introduces limitations on speed and overall performance [10]. Although cranes travel vertically and horizontally simultaneously, the actual travel time equals the maximum of the horizontal and vertical travel time (Chebyshev distance metric) [5].

In Cartesian AS/RS technologies, the maximum possible throughput is achieved when the shape of the system is considered to be L-square (the time to reach the furthest location on x-axis is equal to the time to reach the furthest location on y-axis) [11,12]. Although a good balance between rack height and length can help in reducing travel times, this solution is still insufficient to improve travel times significantly. Another limitation is due to the insufficient mass ratio between the transport device and the transported loads. The reason behind this poor mass ratio is mainly related to the serial structure of the storage and retrieval device [18]. It is crucial to design an AS/RS in such a way that it can efficiently handle current and future demand requirements while avoiding bottlenecks and overcapacity. Due to the inflexibility of the physical layout and the equipment, it is essential to design it right at once [5].

1.3. Wire-driven robots: a promising technology

In the last two decades, a considerable amount of research has focused on developing wire- (also called cable-) driven manipulators, which are parallel manipulators that adopt flexible cables instead of rigid limbs [14]. Wire-driven parallel manipulators possess some intrinsic advantages over rigid parallel manipulators, such as simple structure, large workspace, high load-weight ratio, and good dynamic performance. Accordingly, wire-driven parallel manipulators have been increasingly and widely used in applications, such as astronomical observation, structure building device, rescue, service or rehabilitation, and multiple aerial robots [14]. In the case of AS/RS, some authors [15,16] recently investigated breakthrough solutions that take advantage of the special properties of wire-driven manipulators to realize revolutionary storage and retrieval machines for high racks. Our article builds on the work by [15]. More particularly, we provide a high-level description of the basic components and the mechatronic design of an innovative stacker crane based on a wire-driven storage and retrieval machine. We design the control architecture that allows handling mini-load operations based on a parallel, wire-driven manipulator. We validate the suggested control architecture using a simulation software specifically developed for this purpose.

1.4. Simulation and performance evaluation of AS/RS

Simulation comprises an indispensable set of technological tools and methods for the successful implementation of digital manufacturing, since it allows for the experimentation and validation of product, process and system design and configuration [17]. In literature, most authors focus on the evaluation of the performance of single aisle AS/RSs with one I/O-point. Travel time estimates for both single and dual command cycles in different types of AS/RS configurations are an appropriate analytical tool for comparing control rules and storage assignment policies. Simulation enables performing more extensive experiments under various stochastic conditions. To evaluate the design and control rules of an AS/RS, several performance measures are reviewed in [5]. However, as we suggest an innovative wire-driven S/R machine, existing formulas are not suitable to evaluate the performance of
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