PLUG-AND-WORK MATERIAL HANDLING SYSTEMS

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Abstract

One disadvantage of automated material handling systems is their relative inflexibility: once racks are installed and conveyors are laid, making even minor changes to a system can be cumbersome and expensive. However, recent progress in the capabilities and cost of basic system components, such as controllers, drives, and sensors, has made possible a new class of material handling systems having a much higher degree of flexibility. We propose underlying design principles for such systems and describe several prototype "plug-and-work" systems, which feature decentralized control and ease of reconfiguration.

1 Current Challenges

The companies that comprise the Material Handling Industry are conservative by nature, and for good reason: heavy loads must be handled without injury; large volumes of different items must be handled without damage or loss; and picking, packing and inventory tracking must be done without error. It comes as no surprise, then, that manufacturers and users tend to be careful when designing and implementing new systems.

Although the industry has implemented hundreds of successful automated material handling systems in the past, there are signs that business is or will be getting more difficult. For instance, a survey in Germany showed that users of automated material handling systems have reduced their investments in automated systems or are planning to "de-automate" significantly (see Figure 1). Although this study is now somewhat dated, we believe its underlying message is still valid.

The study contends that many users consider automated systems too inflexible to cope with rapidly changing demands in structure, volume, and processes of today's material handling processes. But what is it, exactly, that makes a modern, automated material handling system inflexible? We believe the following logic is behind this judgment: (1) A system is inflexible because it is time consuming and expensive to change in response to new requirements; and (2) current systems are difficult to change because functionality is spread over several levels of information, electrical, and mechanical networks, all of which must be changed simultaneously to provide new functionality.

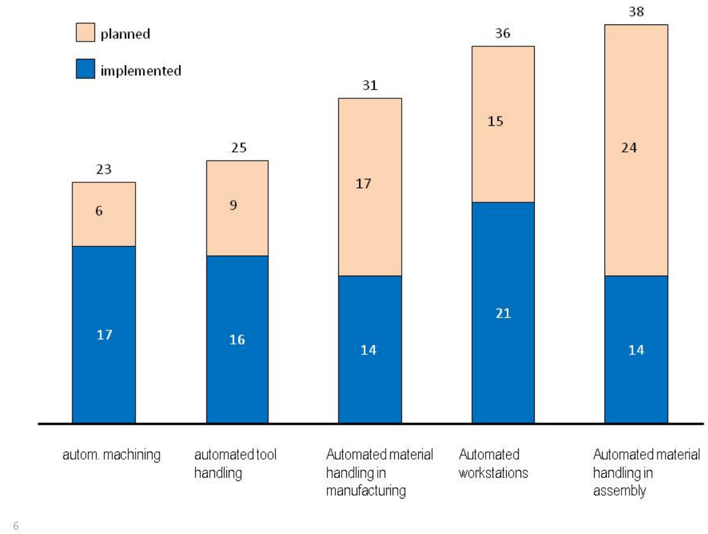

Figure 1: Reduction in automation in several production areas, according to ISI [3]. Statistics indicate the percentage of respondents who were planning or who had already implemented a reduction in automation.

1.1 Current (inflexible) designs

We illustrate the point with a small example: Suppose an automated pallet warehouse retrieves items with an AS/RS-machine and moves them by conveyor to a transfer-carriage, which moves the pallet to the assigned picking position. After picking, the pallet is returned to the rack. The picked parts then move to a sorting and consolidation area. Suppose the need for higher picking capacity makes necessary an additional picking location, and that (luckily) there is enough space to accommodate that position. Which tasks must be performed to make this simple extension?

First, additional sensors must be installed at the new stopping position. They signal to the PLC when the transfer-carriage is positioned correctly at the handover position. Second, let us assume that, in keeping with current practice, the necessary drives, rollers, sensors and structure-elements are already combined into one module. This module must be installed at the additional position. Third, the wiring between the drives, sensors of the picking position, and the sensors of the transfer-carriage one end and the control cabinet on the other end have to be installed and connected. If necessary, new control boxes have to be added to provide the required input-ouput ports for the PLC. Fourth, the input and output ports must be connected to the logic of the PLC. Essentially, this requires adding another position in the scheduling logic; that is, adding the sensors of the new position in the "check for free location" logic by connecting the port numbers of the sensors with the logical view of the added position.

When the new position is actually used, the code for moving the transfer-carriage to the new position has to be updated to include the new position as well as for the return of the pallet. Finally, the user-interface of the PLC has to be updated with the status of the new position.

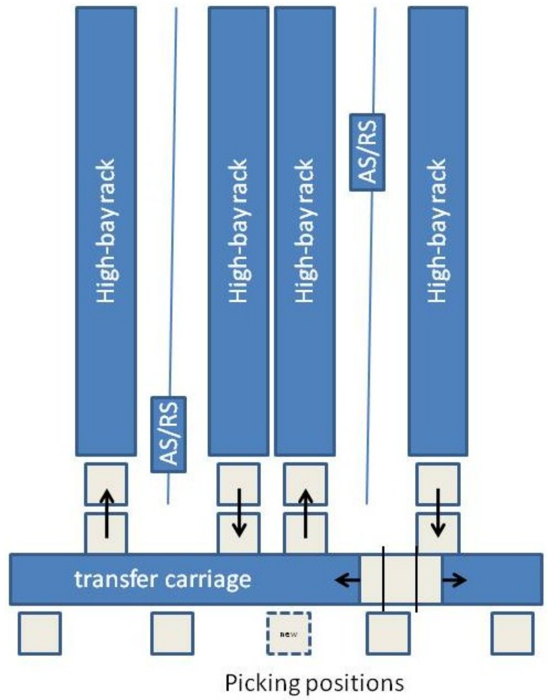

Figure 2: High-bay warehouse with picking positions ("new" indicates added picking position).

In order to do all this, the company must employ or hire personnel able to do the electrical work, and to link the physical view (mechanical, electrical) with the software logic. This is very important because the function of the system is distributed over several elements which are connected by a central control logic, usually implemented in a PLC. Documentation brings together the several areas of expertise needed to perform the necessary tasks to change the mechanical design, the wiring, sensors, drives, and controlling logic. These activities take at least one day, depending on the amount of work necessary for wiring and coding, and they usually cannot be done by the system operators. Instead, contractors or qualified personnel have to be brought to the site, along with the necessary equipment and material.

We hope the reader acknowledges that such effort for such a small system change is unappealing at best, and that it supports the assertion that many automated material handling systems are "inflexible."

1.2 Outsourcing

Another obstacle to widespread adoption of automated material handling systems is the recent trend among many retailers and other distributors to outsource their logistics requirements to third-party logistics providers (3PLs). To its credit, outsourcing tends to generate an improved cost-position through lower cost labor and pooling resources of multi-client warehouses. These outsourcing contracts tend to last frequently for 3–5 years [7], a time span which typically does not allow full repayment of investments in automated material handling systems and warehouses. Because the risk of a non-renewal of the contract is high and re-use of these facilities is not guaranteed, buildings and equipment are often leased with back-to-back contracts. If the 3PL loses the contract, everything is returned to the lease provider. Although in practice, contractual relations with 3PLs usually last much longer than the minimum contract duration, the risk of an investment in automated material handling systems is borne solely by the 3PL, and is often too high to justify the benefit.

A related phenomenon is off- or nearshoring, in which manufacturing or logistics services are moved away from high-wage countries in North America and western Europe toward lower-wage countries. The availability of low cost labor in developing countries suppresses what would otherwise be an economic climate (high wages) favorable to automated material handling.

1.3 Lean warehousing and production

The application of lean principles to warehousing is commonly believed to be another means to increase productivity [4]. The major theme of this approach lies in the standardization of processes, a careful observation of the quality and efficiency of process execution, and a closely linked improvement loop. Improvement workshops ideally should be carried out and implemented by the shop floor team itself. Automated systems — for data processing and material handling — prohibit the timely implementation of process innovations developed by the team, thus frustrating the workforce and reducing the number of potential improvement loops.

2 Opportunities through New Technology

The observations above paint a fairly bleak picture for the material handling industry, but we believe great opportunities still exist, if much more flexible systems can be created. In the past, creating a material handling system for future requirements consisted of an effort to better forecast those requirements and building new systems to meet them. This frequently resulted in more expensive installations, which sometimes still were not able to adapt to future (unforseen) requirements.

We advocate another approach: The same degree of flexibility that is available for simple electronics should be achieved with more highly integrated, automated material handling systems. Ultimately, the setup, adoption and usage must be so simple that new automated systems can compete in flexibility and reusability with non-automated systems. In order to achieve this goal, such systems must have *properties* similar those in modern computing systems:

What You See is What You Get (WSYWYG): The visible, physical system is all the user should care about. There should be no need to synchronize a physical layout with wiring and the software that contains the control logic.

Plug-and-Play (Plug-and-Work)-capability: Once the material handling system is physically configured, everything is done. New components are added by simple insertion.

Scalability: The system can be up- or downsized in order to adapt to changing performance requirements.

Reconfigurability: The operators must be able to change the system themselves, without the help of electricians or programmers. Changing the systems configuration must be possible within minutes, or at most a few hours.

Reliability through in-place replacement: In order to achieve high reliability, which is characteristic of tightly integrated material handling systems, failing components must be easily replaced, and must not require resetting the whole system. The system detects its own failures and configures itself for repair.

Inherent safety: The system may not endanger the people around it. Transported or stored goods may never be damaged or lost.

Resource efficiency: Through easy reusability and by only operating those modules, that are currently needed, less energy for operation and fewer resources for manufacturing the equipment are used.

Self adaptability: The system should be able to adapt, within the limits of its physical representation, to changes in the patterns and quantities of the material flow. Ideally, the system would detect these changes in flow and be able to adapt itself accordingly.

These requirements suggest a number of attributes for new designs, which we call *design patterns* of plug-and-work material handling systems.

Modularity: The system should consist of highly independent modules, which supplement each other in order to perform the material handling task. The modules can be combined easily in order to create a system. The links between the modules are established by the modules themselves.

Function Integration: Each module of the material handling system contains all functions necessary to perform its task. This usually includes, but is not limited to, identifying loads to be moved, deriving the destination in the system, recognizing the conditions of surrounding elements, moving goods in the appropriate direction, and passing appropriate information to surrounding modules or destinations.

Decentralized Control: The actions of the modules are controlled by their own controllers.

Interaction: Adjacent modules freely exchange information and goods. There is no central instance or master module with this as a special task.

Standardized physical and information interfaces: A major obstacle for reconfiguring automated material handling systems is the need to synchronize functionality of sensors, drives, controllers and mechanical components, which makes necessary high-level interfaces to connect the modules with each other. New systems should be able to exchange information on a function-based level, thus avoiding the problem of synchronizing parts of the system.

3 Example Systems

To make these ideas more clear, we describe some examples of ongoing research projects, which are in various stages of development. These prototype systems are intended to better understand the concepts, of course, but also to serve as a point of discussion with manufacturers and users of material handling automation.

3.1 SmartRack

The *SmartRack* is a flow rack with HF-RFID sensors in each channel or slot. Bins in each channel are equipped with the matching RFID-tags, which contain all necessary information about the parts as well as their origin and their destination. Bins in the rack have a unique ID, and the current status is transferred to a web-service, which allows the supplier to get current inventory and to control production and resupply accordingly. This simple approach makes it possible quickly to initiate a VMI-relationship without the need to connect different ERP systems, which can take several months. The design is simple, but effective: Track the bins in the rack and transfer this information on request to the supplier.

Figure 3: The SmartRack

The SmartRack is modular because more racks can easily be added if more part numbers must be stored. SmartRack integrates all functions necessary to create the decentralized, physical material flow via a micro-controller in each rack which allows information to be exchanged on a higher level between the user and the system.

3.2 Flexconveyor

The *Flexconveyor* [5] is a more complete implementation of plug-and-work design. The Flexconveyor is a modular, unit-sized conveyor, which can be combined with other modules to create a conveyor network. Each module is able to convey in the four cardinal directions (north, south, east, west). The modules are connected by a serial connection, which is used to exchange all necessary information between adjacent modules. Each module uses lightbeams to detect any bins present and has an RFID reader, which identifies the bins and determines the destination.

In order to achieve our goals, the modules exchange information with each other on several levels. The first is topological—when each module is connected, modules pass messages to discover or update the existing topology. Next is routing information: During the message passing, each module executes an algorithm to update connections of its neighbors (and their neighbors, and so on), as well as the the distance (measured in modules) to each reachable module. This information is exchanged continuously between adjacent neighbors, leading quickly to complete routing information, which shows which direction an individual module should convey in order to send its bin to its destination most efficiently.

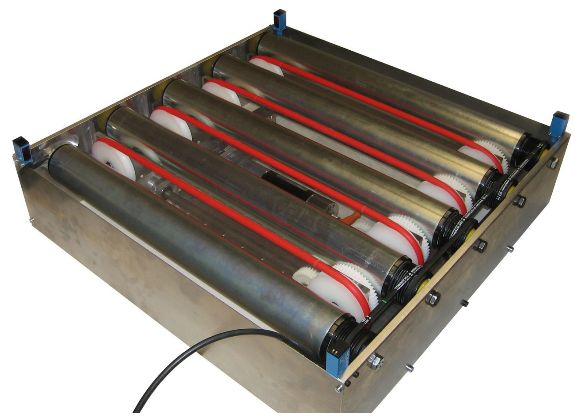

Figure 4: The Flexconveyor.

When a bin enters a module, the module reads its RFID tag and determines the target module. Based on the routing matrix, the appropriate port is selected, which is the link with the shortest distance to the destination. Then a "telegram" is sent to the respective port, asking whether the route towards the destination is available. The next module forwards this telegram to its neighbor, and so on, until the destination module is reached. The destination then sends back a positive or negative answer to the origin module, which then takes the appropriate action (convey or not). The system is completely decentralized, and may be reconfigured in a matter of minutes [see 5, for details]. The Flexconveyor uses all the design patterns we describe above, except it is not yet able to achieve self adaptibility because the modules must be moved by users.

3.3 KARIS

An extension of the Flexconveyor system is KARIS (a German acronym for Kleinskaliges, Autonomes Redundantes IntralogistikSystem which can be translated as small scale, autonomous, redundant material handling system). Whereas the configuration of a Flexconveyor can only be changed by the operators, KARIS is intended to achieve self-adaptibilty and to provide a wider range of scalability and reconfigurability. The idea is also to bridge the gap between AGV-systems and conveyors in order to acheive very different levels of throughput. The KARIS elements are autonomous and are able to perform a simple material handling task: moving bins of the size 400x600mm. In order to achieve this, there is basically a Flexconveyor on the top. The middle level contains laser-scanners and controllers; the bottom level contains drives and the energy system. Energy is provided contactless and can be stored in a battery. The transportation orders are received from a dispatcher, which might provide the link to a Warehouse Management System. Localization of the elements is based on their integrated laser scanners and does not require landmarks.

For low traffic intensity, bins are transported separately; if traffic intensity increases, the elements can form conveyors, much like the Flexconveyor. Larger items, such as pallets, can be moved by a group of four elements. Furmans et al. [1] argued that a material handling system consisting of SmartRacks and KARIS elements has significant benefits if applied in a production environment.

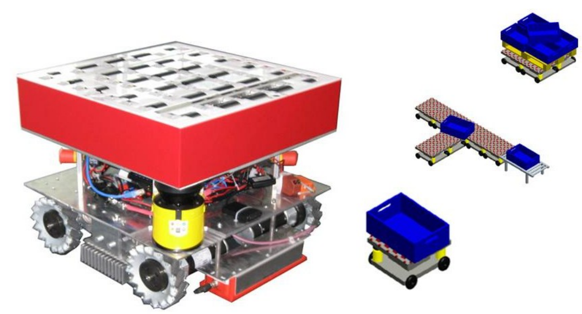

Figure 5: Left: Version 2 of KARIS; right, one element moving a bin, seven elements configured as conveyor, four vehicles moving a pallet.

KARIS elements are completely mobile in a warehouse or production environment. A coordinated research project between several companies in Germany, the University of Freiburg, and the Karlsruhe Institute of Technology is currently underway.

3.4 Puzzle-Based Storage Systems

A second extension of the Flexconveyor concept is puzzle-based storage systems [2, 8, 9, 10], in which items move according to a "slide puzzle architecture." Implementations based on this architecture have been proposed by Agile Systems, Inc. (the NAVSTORS and NAVPAK systems, developed for the U.S. Navy) and Ito Denki, which developed a prototype tote-handling system that was never deployed. Although these implementations did not adhere strictly to the plug-and-work design concept, such an implementation would be easy with the Flexconveyor.

Two of the authors (Furmans and Gue) are currently working on an extended version of puzzle-based systems, which is different in that it allows simultaneous extraction and replenishment of multiple totes or pallets. The building block of the system is a Flexconveyor module (or similar unit-handler), which communicates its state and intentions with its neighbors. The system adheres to the plug-and-work paradigm in that it is decentralized and easy to reconfigure.

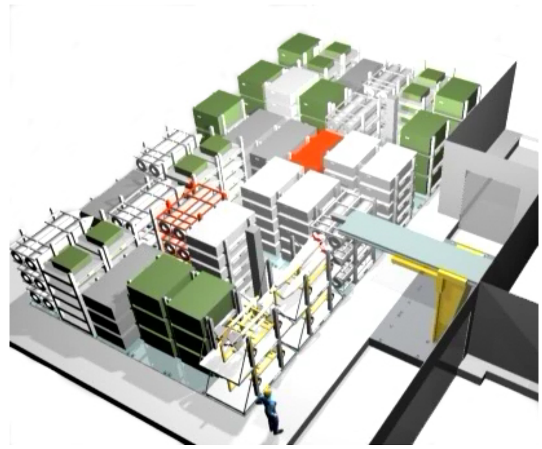

Figure 6: The NAVSTORS system.

4 Opportunities

We acknowledge that a component-based, plug-and-work system is likely to be more expensive than current material handling systems, because more technology is used in each module. But to dismiss the concept on the basis of cost is to miss the point that a major objection to adopting automated material handling systems is inflexibility, not high cost. Plug-and-work systems offer a way to overcome this objection.

There are reasons to believe that such systems will be more affordable in the future:

1. Progress in the technology of sensors, drives and controllers has made them very cheap, especially if consumer quality is good enough for the application. When the market is large enough, economies of scale could partially compensate for the larger number of components used. For example,

    - The performance of processors doubles every 1.5 years while prices remain approximately constant.
    - Prices for NAND-memory fell between 2004 and 2009 from $10/MB to $1/MB.
    - The price for Li-Ion batteries has fallen from $3.19/Wh to $0.28/Wh in 2005, while the density has increased from 88 Wh/kg to 202 Wh/kg.
    - Prices for NdFeB-magnets which are the most important parts of permanent-magnet drives have fallen to 20% of the 1983 price level [6].

2. Reusability of the modules and the option to vary the number of modules according to system load mitigates the need to oversize a system at early stages of deployment.

3. Cost for the design and the setup of the system goes down, because the setup can be done by the user.

4. The cost for system changes is lower, because operators no longer need suppliers to make changes, unless purchasing more or different modules is required.

We have argued that the material handling industry is at the edge of potentially dramatic change in the way it designs and builds automated systems. If we are right, if prices for core components of automated systems continue to fall, and if the capabilities of those components continue to increase, a new breed of highly flexible, decentralized material handling systems is possible.

Because these systems are not centrally controlled, they will require new theoretical models and methods of analysis. The key to flexibility in our opinion is decentralized control, which alone is able to deal with the complexity of changes in which functionality is distributed over several system layers. Our research leads us to believe that the material handling research community has extensive knowledge about the optimization and control of centrally controlled systems, but that there is a general lack of knowledge about the behavior and control of decentralized systems, such as the ones we describe above. We invite our colleagues to join us in defining and answering the fundamental questions of what could be the new era of material handling research.

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