Technology and Policy Challenges to be Met for Introducing Holons into Factory Automation Environments

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Abstract

A holonic system is envisioned to have a high degree of openness to incorporate new resources at runtime, and is reconfigurable to make new product types with legacy hardware configurations. This paper describes ongoing industrially-geared research into identifying a roadmap (as part of a larger business-case analysis) for introducing the holonic paradigm into the next generation of factory automation environments. The research goal is to formulate a vision of holonic manufacturing grounded on inter-dependent arguments. First the 'policy' based on understanding the implications of adopting this new factory automation approach on micro- and macro-economic decision-making. Second the 'technology' based on how to best develop and deploy holons by pragmatic use of intelligent software agents.

1. Introduction

Nowadays, manufacturing and logistics companies are facing a rapidly increasing demand from consumers for mass-customisation. In other words, they are being asked to provide people with products that have been uniquely made to fit that particular person's configuration or taste. Furthermore, people are not prepared to wait long lead times for delivery. Also the proliferation of the Internet means that manufacturing companies need to more closely integrate new e-business tools to work with their suppliers. For example, 'I want, via a website, to order an exclusive mobile phone with a specific coloured face, and incorporate the functionality of GPRS, Bluetooth and have selected Java™ games pre-loaded. This specific configuration is not offered by a standard model'.

Today, this agile scenario of manufacturing and service industries in the telecommunications sector is not feasible because traditional automation systems and business/political thinking are geared to mass production of low-variety goods to give the manufacturer predictable flows of cash and materials through their supply-chain. Often a schedule of the manufacturing operations on a given day is developed well in advance. As the schedule is executed, unexpected events, typical of many production, warehousing and logistic environments, tend to invalidate the schedule and change how operations are managed. These events include introducing rush orders, occurrence of machine failures, incorporation of new multi-function hardware or handling of returned goods.

Furthermore, longer-term pressures are being regularly applied to large businesses in order to reconfigure and consolidate their finance in particular business centres, markets or countries. Also there is a constant demand to re-structure how such a multi-national manufacturing business operates – often in the face of political and socio-economic pressures – to maximise efficiency by taking advantage of a particular country's workforce skills, tax system, market characteristics or incentive schemes.

In other words, manufacturing businesses are being pushed, by market forces and economic/political factors, to provide mass-customisation of their product families and to react more quickly to consumer demands, often within the scope of their existing factory automation infrastructures. Several approaches to solve these problems exist; this paper presents one such solution, namely *holonic manufacturing* [1] [2]. The idea of a *holon* was initially postulated by Koestler [3] to describe how many natural and manmade organisations displayed characteristics where every element of the organisation is simultaneously a whole independent system (it has autonomy) and is part of some larger society (it must cooperate with other holons to solve its problems).

The term holon is composed of the Greek word *holos* to mean whole, with an ending *on*, as in proton, to indicate that the entity is a particle. The application of this holonic approach to manufacturing is envisioned to facilitate the next generation of factory automation systems where every decision-making element is a holon. In Marik *et al* [4], a holon is defined as "… autonomous cooperative unit which can be considered as an elementary building block of manufacturing systems with decentralised control". We wish to enhance this definition by adding some context to the purpose of adopting the holonic paradigm. Put simply:

A holon, once situated in its manufacturing and business environment, uses intelligence, coordination, independence and decentralisation in order to best meet the policy and technology challenges associated with agile manufacturing.

Holons will be used to encompass smart machine control, planning/scheduling of resources, and integration with other factory information and supply chain management systems. However a key drawback to the deployment of the new model of multi-national manufacturing, based on the research findings into holonics, is that there is often no associated strategy to migrate the conceptual holon model into real factories with their heterogeneous automation and business information systems. The paper presents our initial views on the 'policy' and 'technology' challenges that are posed by having to create such a migration strategy.

2. Policy Challenges for using Holons

The challenges facing those seeking to implement holonic manufacturing are similar in many ways to those faced by implementers of simple automation. It is most cost-effective for companies to implement holonic manufacturing in countries with high labour costs, as the effective automation of the plant will reduce the need for human employees. These countries also tend to rank higher in terms of educational level, making the acquisition of staff with the technical knowledge to maintain the holons less problematic. In addition, many such countries, having experienced a gradual shift in the manufacturing base to countries with lower labour costs, have implemented schemes to reward companies investing in manufacturing operations with tax deductions, reductions in rent, sizeable loans or other such advantages. The investment involved in implementing holonic manufacturing will often be sizeable – at least initially – so it would not be surprising for companies to seek out locations where these benefits might be accrued in order to reduce their outlay.

However, the countries with higher labour costs also tend to have stronger trade unions. The reaction to reductions in the workforce due to automating or partly automating existing factories has been well-documented in a number of countries since the industrial revolution; the modern trade unions can create many problems for companies, including strike action, lobbying and even sabotage. Even when existing staff are not made redundant – for example, in the case of an entirely new holonic plant being built – trade unions and local groups may well protest at the financial benefits being offered to companies who do not plan to create what they see as a proportional number of jobs. To the regional authority, however, the investment may be financially defensible on the grounds of the employment they expect to be indirectly created. Supply, support and customer infrastructure frequently grows up around areas where nodes of specialised manufacturing have been founded, potentially creating employment in an area in which most of the production is nevertheless automated.

Within the company itself, the advantages offered by holonic manufacturing over simple automation can also present challenges to company strategy. Mass-customisation using holonic manufacturing is one such example. The ability of a holonic process to assemble items using individually selected configurations of components from a variety of options – and to respond quickly to changes in the orders – is superior to that of a human workforce. The ability of such a system to do this results in a quicker to-market time for customised products. The Spanish clothing company Zara, which owns its own production, has reduced its product-to-market time to the extent that it can change its on-shelf products every two weeks and flex production to respond to customer demand. Holonic manufacturing would allow this level of flexibility – and more – in a wide range of industries. The challenges to company strategy revolve around optimising these advantages. A quicker to-market time can best be exploited if the factory is situated in-market. This may well involve a shift in production from one country to another, and changes being made to the company's supply chain as a result. At a time when mass production in China and India is seen as a threat to smaller industries everywhere else, the speed of production of individually customised products can be seen as a potential advantage in smaller markets. For a company with this facility, maximising the advantages offered may require a radical re-think of the location of its assets, the length of its supply chain and the sourcing of its components.

Economically, holonic manufacturing could make sense both in larger economies with expensive labour forces and in smaller ones which, unable to compete with the scale of production elsewhere, have been forced instead to move into customised niches or to assemble goods from abroad. It is frequently cheaper to transport mass-produced components than finished products; the holonic assembly of customised goods using foreign components, in configurations specified locally, will not only result in a faster to-market time for specified goods but could also reduce shipping costs.

Legislative demands can also be addressed using holonic systems. The European Union's Waste of Electrical and Electronic Equipment (WEEE) Directive places responsibility for the safe disposal of electronic and electrical equipment in the hands of the company that created – or 'branded' – them. British Telecom (BT) no longer produces telephones itself, but instead has them made by a third party and the BT logo affixed. Under the legislation, BT is therefore responsible for their disposal at their end-of-life. Automated, holonic disassembly of large numbers of products, their components tagged and recognised using RFID technology, becomes possible on a large scale. These components can potentially be reused, recycled or safely disposed of depending on their material and condition. This system becomes even more advantageous when considering the toxic nature of some components in products requiring disassembly at their end-of-life, when a properly tasked, automated system is preferable to a human one. What might previously have been considered an accompanying disadvantage of moving to a location with such legislation thus becomes less problematic when implementing new, holonic technology.

The responsiveness and agility of holonic systems have long been held up as a key asset. In political terms, this can take on a new significance when considering the added resilience this can provide. In locations where the company suspects there to be an increased risk of terrorism or an attempt to sabotage production, the agility of a holonic system may help to continue production even when some holons have been destroyed. The system, recognising that some holons no longer function or that a bottleneck is occurring in production, will re-route components through the production process so an optimum solution for continued production is quickly found using the remaining assets.

The key policy challenges in implementing holonic manufacturing revolve largely around their replacement of human workers, the initial cost of implementation and the need to find qualified support staff to work with the machines. The benefits of implementing a holonic system may include reducing high labour costs without sacrificing location, increased safety, resilience of production and more effectively competing with mass produced goods elsewhere. The drawbacks, however, will include the initial cost and the potentially hostile reaction to reductions in the labour force. In an era in which the company's ethical responsibility to society is increasingly scrutinised and contested, increasing unemployment in favour of automation is a highly unpopular move. The need to prove the political and economic benefits of moving to holonic production therefore becomes more pressing. Demonstrating downstream benefits to the area, the reduced risk to workers or the positive effects of the technology on the knowledge-based economy are potential avenues to explore for companies seeking to weigh the costs of implementing holonic production against its benefits. Against this, a company must place its need to best exploit the advantages it can gain from holonic manufacturing. This may include a dramatic change in the company's structure, as it changes markets, forms new alliances and optimises its supply chain, potentially streamlining and ridding itself of capabilities it no longer needs. While the benefits holonic manufacturing offers are legion, the greatest challenge to a company seeking to implement it will be to identify/make all the changes necessary to capture value from those benefits.

3. Technology Challenges for using Holons

Existing factory control systems often adopt a centralised architecture and rely upon a Programmable Logic Controller (PLC) to read data in from electronic sensors on the shop-floor, select appropriate actions and issue commands back to actuators. In some modern factories, personal computers are being connected to the PLCs via Ethernet to provide more long-term and sophisticated decision-making such as performing fault recognition on some hardware. However the opportunities to reconfigure how the factory machinery operates are still very limited (e.g. take the control system off-line, encode a new strategy, compile it down into ladder logic, push it onto the PLC, bring back on-line and test). This lack of cohesion means that agility in the automation system is rather poor. Two of the major technological challenges to having 'on the cheap' agility relate to the smart interaction of entities inside the business, and to the adaptability of the processes each of the entities perform.

Questions associated with the smart interaction of entities within the manufacturing business to achieve agility include: How can autonomous machines, tools, raw materials, knowledge servers, manufacturing cells, and enterprises interact intelligently in order to coordinate their activities into a coherent whole when trying to make a rich variety of products and deliver them into the market? How can the knowledge required to facilitate this interaction be represented, exchanged and processed efficiently? How can manufacture recipes be formulated effectively in a resource independent manner, and how can the goals within this recipe be associated with roles and be assigned to physical processes on a shop-floor? How can people and legacy hardware/software be integrated effectively? In particular within a cooperate framework, huge efforts have been made to establish ERP systems and eBusiness solutions to gather, process and provide factory information to enable people and machines to work towards a common goal. Still the problem of pulling all these diverse sub-systems together remains difficult due to the highly dynamic nature of tomorrow's factories while they strive for agility.

Questions concerning the adaptive nature of manufacturing processes include: How are complex distributed manufacturing processes modelled in terms of pro-active entities with situational awareness that can interoperate with other shop-floor entities and diverse processes to monitor their environment and change their behaviour on demand? This transformation of behaviour must be achieved in real-time and without loss of production capacity, on a dynamic basis, in order to make, transport, store and re-use an ever-changing set of products. How can these processes and the equipment that support these processes cope with such change? What new ideas need to be developed to implement this new generation of agile processes based on existing models and technologies?

While several approaches to having agile factories exist, automating them and letting the shop-floor entities reconfigure themselves to accomplish this diverse and adaptive functionality still remains a significant problem. We argue that this is principally due to the lack of competence in the control software to handle the inclusion, removal and reconfiguration of machinery, and to tolerate unexpected behaviour by or interactions with other factory sub-systems. To address these challenges we are studying a philosophy based on the notion of a holon. Holonics adds additional features to existing automation technologies:

- Holons enable new metaphors for *coordination* to occur based on approaches like negotiation, auctions or market economies. These interactions happen: (i) to join holons together, (ii) to connect holons and humans, and (iii) to link holons with legacy hardware/software. These collaborations are at a semantic level allowing holons to synchronise tasks, data and resource use. Intelligent user interfaces can be constructed to support smart dialogues with people of varying authority and knowledge of the system. Moreover coalition formation is a powerful technique to 'glue' together holons into virtual societies geared towards supply chain management, outsourcing and so forth. Real-time cooperation between a holon and physical sensors/actuators can be applied to best react to changes upon the shop-floor.
- The *intelligence* of holons is exhibited by how they modify their behaviour to satisfy changing design and organisational objectives, change their decision making processes and operate differently when their environment alters. Holons may use artificial intelligence techniques, e.g. reinforcement learning, to acquire new behaviours and may utilise these behaviours in both reactive and deliberative ways.
- Holon techniques support *decentralisation* at different levels: multi-holon systems are inherently distributed because hardware, services, and knowledge can be scattered throughout the manufacturing business.
- Furthermore *independence* between manufacturing resources and the process associated with making a

product is provided by goal-oriented recipes of how to make, handle, store etc various products will be resident in multiple order holons that could be strewn across several machines in the factory or even over the web.

Therefore, our objective is to move from today's manufacturing systems to the full holonic vision. Though, getting companies to throw away their existing automation, control and execution systems in order to adopt a radical new technology is rather unlikely. Hence we need a migration strategy. We propose that a realistic, low risk and affordable migration strategy towards the holonic vision is:

- Stage 0: Build systems using conventional PLC and software approaches.
- Stage 1: Construct partial holonic systems using a combination of advanced baseline technologies.
- Stage 2a: Depending on the policy challenges, deploy full holonic systems from scratch (green field), or
- Stage 2b: Adapt an existing factory to support a higher degree of holonic behaviour (brown field).

4. A Testbed to Explore Holon Challenges

A testbed to explore, with appropriate engineering rigour, the aforementioned policy and technology challenges to the adoption of holons is a packing cell demonstrator that has been constructed at the Institute for Manufacturing.

From a physical viewpoint, the packing cell comprises a pair of storage units to hold items (currently we use Gillette personal grooming products) while three robots (two anthropomorphic Fanuc M6i robots and a 4-degree-of-movement Fanuc A520i robot) are employed to move items throughout the cell. A gantry robot is used to transport boxes and trays of items between the packing and warehouse cells. A Montrack™ conveyor system with powered shuttles is used to transport items and boxes around the cell. The track (with its independently controlled gates) provides added agility by being able to direct individual shuttles and dynamically assign transport tasks to them. There are also four docking stations where shuttles are held so the appropriate robot can pick and place items into boxes.

In terms of behaviour, this cell is geared towards mass-customisation and enables the customer to select any three of four items (e.g. razor, shaving gel, deodorant or shaving foam), and pack them into one of two box styles. Warehousing facilities provide space to store items and boxes, and so mimic a distribution centre as part of a supply chain. The cell is intended to be agile to changes in order requirements, and be robust to hardware alterations.

Some of the agile manufacturing behaviour that this demonstrator should provide is displayed through simple scenarios. These scenarios include: (i) adding and removing robots from the packing cell and automated re-assignment of packing tasks; (ii) organising the warehouse in a suitable way so that retrieval time is minimised; (iii) having new product types included and letting the declarative recipes be used to dynamically construct a process plan of resources; and (iv) boxes buying and selling items in order to get packed both economically and achieve delivery deadlines.

Though this is a relatively small scale manufacturing system, the degree of sophistication in the cell's control system to provide the desired agility is rather complex. In the authors' opinion, as a result of building several such systems, the challenges raised by coding software to handle the complexity needed to give truly agile behaviour is not adequately supported by today's control infrastructures. Hence there is real demand for the holonic technology. The smartness in the holonic application will be provided using JACK Intelligent Agents™, the flagship product from Agent Oriented Software. The key features of JACK are that:

- It supports a Belief/Desire/Intention execution model and so the developer is not left on their own to construct all the software needed to build and run rational agents.
- It has a rich set of graphical tools for agent design, plan editing and tracing for creating holons' behaviour.
- It has been used to model behaviours in a wide range of distributed domains where actors act both autonomously (in their decision-making and their reasoning about the dynamic nature of the world they live in) and socially (cooperating, competing and negotiating over action).

Agents execute their reactive and deliberative behaviours via pre-compiled plans chosen according to the knowledge an agent has about itself and the world. If a plan fails, the agent executes other plans until the goal is achieved.

5. Conclusions

There are several benefits to companies if they can offer agility. These include the ability to rapidly react to market forces, the ability to corner niche markets quickly, and the ability to charge more money for the value-added services they attach to each of their manufactured goods. However there is a downside: at present it costs a lot of investment to create a factory infrastructure that is agile. So the driving force behind our work is to deliver agility into existing factories without incurring the high set-up costs.

It should be stressed that this is work-in-progress research and is part of Agent Oriented Software's aim to provide high-quality solutions to businesses and government organisations that combine a solid business philosophy with world-class research and technology. The outcomes so far are promising, and the following observations can be made.

From policy and technological perspectives, intelligent software agent technology coupled with the holonic vision form an ideal metaphor for constructing such agile factory strategies. At present, techniques and methodologies to construct and roll-out such technology into real-world industrial control settings are not yet sufficiently mature. A roadmap is being developed to facilitate this maturity.

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