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◆ 특집 ◆ 자동화를 넘어 자율화 (첨단제조를 위한 자율화)

스마트 매뉴팩처링을 위한 자율화

Autonomy for Smart Manufacturing

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Smart manufacturing (SM) considered as a new trend of modern manufacturing helps to meet objectives associated with the productivity, quality, cost and competiveness. It is characterized by decentralized, distributed, networked compositions of autonomous systems. The model of SM is inherited from the organization of the living systems in biology and nature such as ant colony, school of fish, bee's foraging behaviors, and so on. In which, the resources of the manufacturing system are considered as biological organisms, which are autonomous entities so that the manufacturing system has the advanced characteristics inspired from biology such as self-adaptation, self-diagnosis, and self-healing. To prove this concept, a cloud machining system is considered as research object in which internet of things and cloud computing are used to integrate, organize and allocate the machining resources. Artificial life tools are used for cooperation among autonomous elements in the cloud machining system.

Key Words: Smart manufacturing (스마트 매뉴팩처링), Autonomy (자율화), Cognitive agent (인지 에이전트), Swarm intelligence (군집 지능), Cloud machining (클라우드 머시닝)

1. Introduction

The complexity and dynamic of the manufacturing environment are growing due to the changes of product types, suppliers, as well as the unexpected disturbances in the machining or assembly systems such as machine breakdown, malfunction of robot or transporter. Currently, the conventional manufacturing systems, such as the flexible manufacturing systems are unable to adapt to the complexity and dynamic of the manufacturing environment. These systems activate the automatic operations by using the pre-instructed programs and should be stopped to re-program and re-plan in case of disturbances, which reduce the flexibility of the systems and increase the downtime. In order to cope with the changes of the manufacturing environment, new methods and technologies have been proposed in which the distributed manufacturing control system and the biological inspired technologies for implementing this system are remarked. Self-adaptation to disturbances is a crucial issue in the development of intelligent manufacturing systems. It is the ability of a manufacturing system to respond rapidly to disturbances and recover autonomously to keep the manufacturing system running and avoid the manufacturing processes stopping completely. Many methods for the management of disturbances within manufacturing systems were proposed in the literature such as rescheduling, reactive and collaborative approaches.[1] These methods are classified by two criteria: reconfiguration and autonomy.[2] Reconfiguration is to rearrange and restructure manufacturing resources that require the rescheduling method and reconfigurable ability of manufacturing systems. Autonomy allows the system to recover autonomously without modifying scheduling. Reactive and collaborative methods were proposed following this criterion. Reactive method is an autonomous control of an entity to overcome disturbances by itself, while the collaborative method is used for a cooperation of an entity with other entities in order to adapt to disturbances. These methods are suitable for disturbances, which are not necessary to reschedule. In order to implement reactive/collaborative methods, a distributed control architecture is required.[3] The control architecture changes from centralized control of non-intelligent entities in hierarchical structures towards decentralized control of intelligent entities in distributed structures.

This paper presents an autonomous manufacturing system (AMS), in which the AMS structure is a swarm of cognitive agents, in order to improve the system adaptability to disturbances. Consequently, resources on the shop floor such as machine tools, robots, and so on are controlled by corresponding cognitive agents. The AMS is designed with following characteristics for adapting to disturbances:

- Allowing the control system to take an action when the disturbance happens and to continue to operate instead of stopping the manufacturing system completely;
- Equipping the entities in the manufacturing system with the decision-making and self-controlling abilities.

2. Literature review

Manufacturing systems of the future will be characterized by the strong individualization of products under the conditions of value-added processes and high quality services. So, new technologies and methods are researched for the next stage of industrial manufacturing. Numerous researches in the manufacturing field to achieve an intelligent manufacturing have been reported in the literature. The research area can be classified as follows:

- Technologies for the advanced information systems such as manufacturing execution system (MES) and process planning, industrial network, inheritance of data and information and communication technology (ICT) for industry;
- Evolvable hardware/software such as integration of industrial systems, intelligent diagnosis, effective maintenance for equipment and system, hi-tech machinery industry and intelligent sensors;
- Manufacturing system architecture such as international standards, design technology and model of the manufacturing system.

The new trend of the manufacturing system development is to apply autonomous behaviors inspired from biology for the manufacturing systems. Many novel paradigms that are known as intelligent manufacturing systems (IMS) were proposed in the literature. The biological, holonic, and cognitive manufacturing systems are the most remarkable concepts. In the holonic manufacturing system, machines, parts, transporters, and robots of the manufacturing system are called holons, which should have autonomous and cooperative characteristics. The agent technology is used for carrying out this framework because this technology enables the implementation of a distributed manufacturing control.[4] In the biological manufacturing system (BMS), machine tools, transporters, robots, and so on should be seen as biological organisms, which are capable of adapting themselves to environmental changes.[5] In order to realize BMS, agent technology was proposed for carrying out the intelligent behaviors of the system such as the self-organization, evolution and learning. The reinforcement learning method was applied for generating the appropriate rules that determine the intelligent behaviors of machines. In the cognitive manufacturing system, each machine and its process are equipped with cognitive capabilities in order to enable the factory environments to react flexibly and autonomously to the changes, which are similar to human behaviors.[6] A cognitive architecture for manufacturing systems introduced to reach this goal, is named beliefs-desires-intentions.[7] This architecture is based on a human decision-making model from cognitive science that comprises knowledge models, methods for perception and control, methods for planning, and a cognitive perception-action loop.

The above-mentioned IMSs consider the ability to adapt to changes at the management level such as the enterprise resource planning (ERP) and MES as well as changes at the shop floor level. However, the approaches of such systems to practice for solving the changes on the shop floor are still limited in terms of an autonomous way. Currently, the manufacturing systems should be stopped if the disturbances on the shop floor happen. Then, a new schedule generated by the management level is dispatched to the shop floor. Most of the current researches were focused on the rescheduling method for adapting to disturbances within the manufacturing system, while only a few researches were concentrated on reactive/collaborative method with applying agent or cognitive technologies. The paper proposes a different approach called as a cognitive agent based manufacturing system in which the shop floor overcomes the disturbances by agent cooperation without upper-level aids such as the ERP and MES. To increase the autonomous operation scope of agent, the cognitive agent is proposed. The agents use the ant-like pheromone based negotiation mechanism for handling disturbance.

3. Core Technologies for Realizing Smart Manufacturing

3.1 Cognitive technology

The paradigm "cognition" in terms of the manufacturing system denotes that machines and processes are equipped with cognitive capabilities and cognitive controls in order to enable them to increase their scope of autonomous operations. A cognitive control consists of three general actions: perceiving information in the environment, reasoning about those perceptions using existing knowledge, and acting to make a reasoned change to the environment. Cognitive capabilities are perception, reasoning, learning and planning. Manufacturing systems with cognitive capabilities will be much easier to interact and cooperate with, and they will be more robust, flexible and efficient. Learning can be defined as a way to acquire knowledge and skills to adapt the changes, and it is crucial to respond to the dynamic of environment and to improve the system ability to act in the future by taking a better decision and performing better the required actions. Learning is normally performed in result of the decision making process allowing to adjust the decision parameters or to update the behavior rules. In the manufacturing control context, the learning mechanisms are triggered mainly in the situations: the process finishes, the system configuration changes, and unexpected disturbances occur. Reasoning is used in prediction tasks and decision making. Several reasoning mechanisms are used such as causal, temporal, and spatial reasoning which enables the system to solve dynamically changing and more complex tasks. Reasoning plays the main role for autonomous adaptation process of the system where the system adapts to disturbances and changes autonomously.[8]

3.2 Cognitive agent

Agents can be classified such as biological agents (human), robotic agents (autonomous robots), and software agents. In this research, the agent technology is applied to implement distributed systems by set of software agents. Software agents are computer programs that have characteristics such as autonomy, social ability, reactivity, and pro-activeness. The autonomy is an ability of the agent to achieve its goals without any support from the other agents. On the other hand, the interaction between agents is the social ability of agents that is used to get the global goal of the system. The reactivity, which is based on the relation between perception and action, is an ability of agents to respond to the environmental changes. The pro-activeness of agents is an ability to express the goal-directed behaviors. The reactions of agents to the environmental changes are the reactivity or pro-activeness that depends on what kind of agent architecture is applied to develop the agents. With the conventional agent, the reactions of agent to changes of the environment (status of the machine tool) are based on the rules. A synthesis approach of the agent and cognitive technologies are applied to improve the autonomous characteristics of conventional agents. As the result, a smarter agent, namely cognitive agent, is proposed. The cognitive agent is a computer program equipped with artificial cognitive capabilities in order to perform the

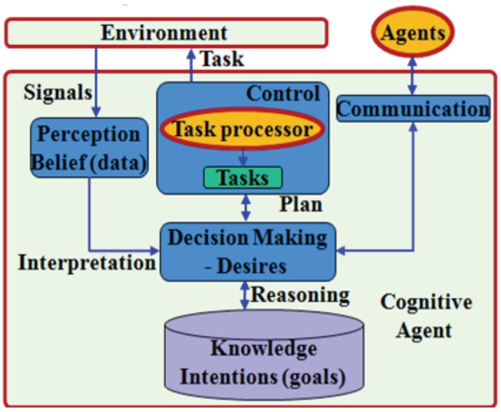

Fig. 1 Architecture of a cognitive agent

cognitive activities which emulate the cognitive behaviors of human such as perception, reasoning and decision making, communication, and learning.[9] Cognitive agents ensure the flexibility of the manufacturing system for adapting to the changes and unexpected disturbances. The cognitive agents implement a cognitive perception-action loop that does not only adapt to the changes of manufacturing system autonomously but also inherits any new optimal plan generated for adapting to disturbances.

The architecture of a cognitive agent is shown in Fig. 1. It consists of five modules: perception, decision making, knowledge, control and communication. The perception module is responsible for data acquisition in the environment. The data in different formats such as visual data, auditory data and vibration data are interpreted into a standard format called belief set. The decision making module is responsible for the agent to make a decision in an autonomous way. The control module processes the plan into tasks and executes the tasks to the environment. The communication module is responsible for interactions between the cognitive agent and the community of agents. The knowledge base module contains intentions, plans, and knowledge base of the agent.

3.3 Swarm intelligence

In the natural environment, a collective intelligence is carried out by simple interactions of individuals. A concept found in the colonies of insects, namely swarm intelligence, exhibits this collective intelligence. Swarm intelligence is established from simple entities which interact locally with each other and with their environment such as colonies of ants, schools of fishes, flocks of birds, and human cooperation.[10] Swarm mechanism is applied to the manufacturing field. In ant colonies, the collective intelligence is given by interactions of individual ants with the limited cognitive abilities expressed by chemical substances called pheromones. One of the collective intelligence of an ant colony is finding the shortest route from the nest to the food source. The first ant finds the food source and returns to the nest leaving behind a pheromone trail. Over time, the evaporation of the pheromone trail begins to reduce its attractive strength. The pheromone evaporation is a criterion for avoiding the convergence to a locally optimal solution. Ants can follow many possible ways from the nest to the food source and back again, but the strengthening of the route making them more attractive is the shortest route. Transferring this principle to the manufacturing field, in manufacturing systems, which are seen as a community of autonomous and cooperative entities, self-organization is carried out by locally matching between machine capabilities and product requirements. Each machine has a pheromone value for a specific operation and the machine with the shortest processing time for a specific operation has the highest pheromone, which is chosen for the operation. In the AMS, the system self-organizes to adapt to disturbances by using the pheromone based agent negotiation mechanism.

3.4 ICT infrastructure

In communication, resources of the manufacturing have the ability of identification, data collection and making a decision autonomously due to an ICT infrastructure. The ICT infrastructure contributes significantly to the success of implementing the AMS. The MES provides an interface between an ERP system and shop-floor controllers for executing the functionalities such as scheduling, order release, quality control, and data acquisition. The ERP system supports almost all business systems whose single database is used for business functions such as production and supply chain management.[11] The ERP system also can be considered as the informational backbone of IT infrastructure for manufacturing system. Radio frequency identification (RFID) technology and the sensor technology related to it have a great potential in changing the way of control, production automation, and special data collection in connection with the higher level such as ERP, supply chain management (SCM), and customer relationship management (CRM). Ubiquitous sensor network (USN) is a tool for collecting production data in real-time constraint. The USN plays the role of monitoring for machine operating status, actual production, and increasing the product quality. A component is called intelligence if it shows advanced characteristics, such as unique identification, communication with the environment, ability to store data about itself, language to display its features or production requirements. As it is inspired from the biological organism of which the information exists within itself, a new approach is to store directly the production data on the component surface by merging the information and component. For the chosen approach, it is necessary to develop the magnetic magnesium (Mg). The Mg used as a sintered material is integrated into an appropriate component. The vision of "feeling" machine components is achieved by attaching multi-sensor system to these components.[12] Intelligent components are the results of applying sensor technologies and the ICT progress that ensure the precise operations and flexibility of the manufacturing system. Ubiquitous computing, ubiquitous networking and ambient intelligence are three representative conceptions that embody the most important aspects of the ubiquitous technology. In ubiquitous computing, the computing devices are embedded into the machine tools so that the operators can interact with the devices at the same time as they interact with the machine tool. In ubiquitous networking, computers and machines can be operated at any place, at any time. Ambient intelligence comes out from the integration of ubiquitous computing and ubiquitous networking. Normally, it represents a well defined space with a certain level of intelligence that results from embedding technology. Being ubiquitous machine, the machine status and machining data of CNC machines can be monitored and controlled with wired/wireless environments, anywhere and anytime. Moreover, prompt notification from CNC machines to mobile phones is automatically realized in emergencies.

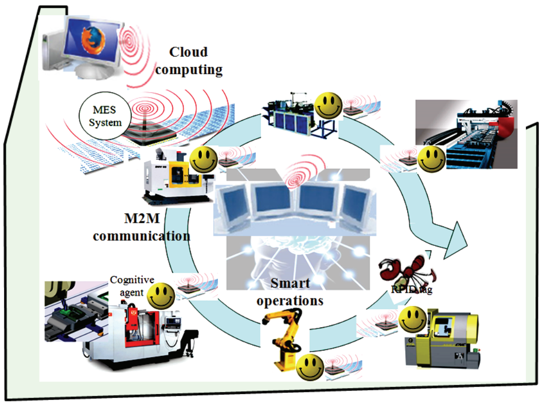

Fig. 2 Concept of an autonomous machining system

Cloud computing is the next step in the evolution of ICT infrastructure as. It enables to realize collaborative design, distributed manufacturing, collective innovation, data mining, semantic web technology, and virtualization. In smart manufacturing, cloud computing enables to develop products quickly with minimum costs through a social networking. Model of the cloud computing system is parallel and distribution which consists of a collection of inter-connected physical and virtualized service pools of design and manufacturing resources. The manufacturing cloud service can offer capabilities for design and manufacturing solutions at certain levels, such as manufacturing cells, general purpose machine tools, and standardized machine components.[13]

4. Autonomous Manufacturing System

4.1 Concept of AMS

The architecture of a machining system based on cognitive agents for adapting to disturbances is shown in Fig. 2. A multi-agent system was developed to keep the manufacturing process running when disturbances appear.

In this application, resources of the machining shop are controlled by cognitive agents in the case of disturbances; otherwise, the MES controls the shop floor. Cognitive agents are divided into functional agents including work-piece agent, transporter agent, machine agent, and robot agent. This division is based on functions which agents undertake in the machining shop. Work-piece agent manages the processing state of a work-piece. Each work-piece is assigned by an identification number stored in the RFID tag that was attached on the work-piece. Every machine on the shop floor is represented by a machine agent. This machine agent has knowledge about its machine's physical, process capabilities, probable tooling and schedule. The machine agent receives the sensor information from the machine about the machine status and processes. This enables the machine agent to inform the work-piece agent when the processing starts and in particular, when the processing ends and the work-piece leaves the machine. The transporter agent contains routings of the transporter, consequently, interacting with the work-piece agent to transfer the work-piece to the corresponding machine tool for processes. The robot agent contains the information of the robot, about the operations, availability, and interactions with the machine agent to put or take the work-piece to the machine tool. In the smart manufacturing, the cloud computing are proposed for integrating and reallocating the machining resources.

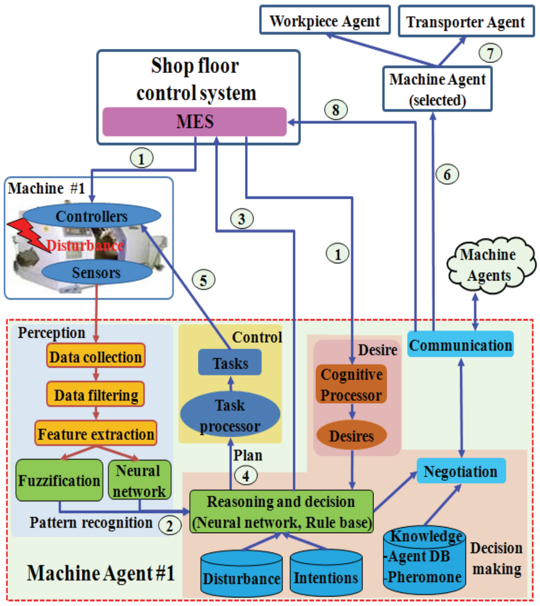

Fig. 3 Mechanism for adapting to disturbances

4.2 Working behavior within AMS

Fig. 3 illustrates the mechanism of cognitive agents to adapt to the disturbance happened at the machine tool. At the beginning, the MES sends a task command to both of the controllers and cognitive agent (denoted by 1). The cognitive processor identifies the goals and transforms them into the desires. The machining shop state is updated by the monitoring module. This module then filters the data to obtain the information corresponding to the responsibilities of the agent. In case disturbances occur, the data are categorized into high and low frequencies through a feature extraction unit. Depending on the types of high or low frequency signal, fuzzy logic is used for diagnosis with low frequencies, and neural network is used for high frequencies. Diagnosis results report the machining shop states: disturbed or normal status (denoted by 2). The planner compares the data from the output of the diagnosis module with the desired goals. If the data reach the desired goals, a message is sent to the MES to report the normal state of the machine (denoted by 3), and the shop floor continues running. Otherwise, the machine agent makes a decision based on the disturbance classification. If the disturbance belongs to non-negotiation type, the decision maker generates a new plan based on the data, desires and intentions (denoted by 4). This plan is directly done by the machine in which the disturbance happens (denoted by 5). This case is illustrated by the disturbance such as tool wear where the machine agent adjusts cutting conditions without affecting to the quality of product. In case the disturbance belongs to the negotiation such as the machine breakdown, this plan is done by another machine. The cognitive agent implements a negotiation with other agents. It sends a request for help to all machine agents. The best solution is chosen based on the evaluation of alternative machine agents in case many machine agents satisfy the requirements. The negotiation mechanism is based on the ant colony technique. The job of the disturbed machine is then performed by another machine in order to keep the manufacturing system running (denoted by 6). The selected agent sends a message to the work-piece agent and transporter agent (denoted by 7) to report that it performs the work of the machine in which the disturbance happens.

The machining system uses the previous plan when the disturbed machine is restored. This solution is applied to disturbances, which take a short time for recovery. In case the disturbances cause a long recovering time or the negotiation among agents does not have any solution, the request is sent to the MES for rescheduling (denoted by

8). If disturbances occur with the robot and transporter such as the malfunction of controllers, the robot agent or transporter agent depends on the disturbed level to use a non-negotiable plan or a negotiable plan or request rescheduling for overcoming disturbances.

4.3 Implementation of AMS

The cognitive agents were developed using the .NET platform and C#. The system architecture of the biology inspired machining shop is shown in Fig. 4. It points out the three kernel issues to implement the cognitive agents, which are the interaction protocol, agent behaviors, and database (DB) as well as the information flow among components in the system for carrying out the functionalities. The agent interacts with the MES and the other agents via the extensible markup language (XML) messages. The process control protocol (OPC) for linking and embedding objects is used for communicating the agent with the programmable logic controllers (PLC) which connect to the physical devices on the machining shop such as sensors, alarm device, and the controlled machine. The databases, including the processing information, the agent addresses for communicating in the network, the pheromone values of the tasks related to the machine agents, and the disturbance DB, were built using SQL Server^{TM}2005. The agent uses the “search” method to diagnose and classify the disturbance. According to the disturbance type, the agent reasons to make a decision using the “adjust” or “collaboration” methods. In collaboration, the agents generate the pheromone value of the assigned task using the “calculate” method. Then, the “negotiate” process is carried out among agents to find the agent with the highest pheromone value for carrying out the task.

The screen shot of the developed system in the case of tool wear is shown in Fig. 5. The machine agent #1 gets the disturbance signal from the PLC #1 through KEPServerEx^{TM} software (denoted by 1). Then, the disturbance is diagnosed (denoted by 2). If the disturbance belongs to the non-negotiation type such as the tool wear (denoted by 3), the agent adjusts the cutting parameters. After changing the parameters newly (denoted by 4), the machine agent sends these parameters to the controller of the machine. The experimental results prove that the mechanism of the proposed system enables

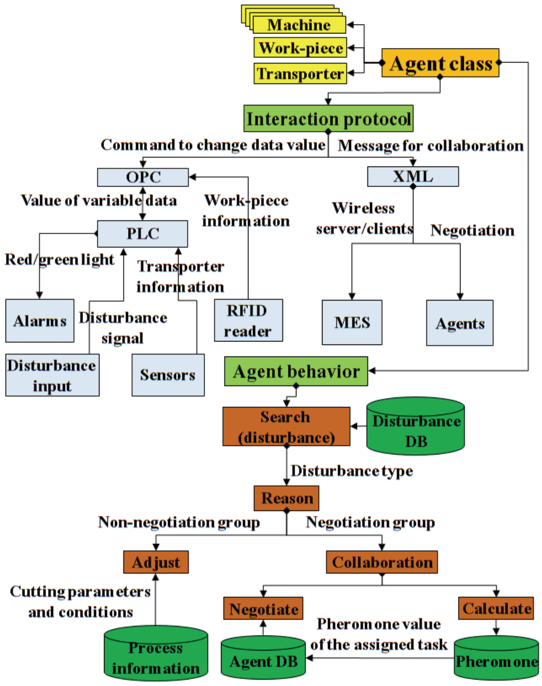

Fig. 4 System architecture of the machining shop

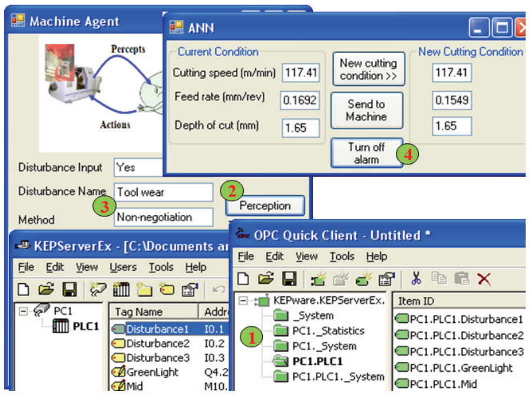

Fig. 5 Screen shot of the system in the case of tool wear

the system to adapt to the disturbances successfully. Through that, the manufacturing productivity is increased.

5. Conclusion

Globalization, unpredictable markets, increased products customization and frequent changes in products, production technologies and manufacturing systems has become a complexity in today’s manufacturing environment. One key strategy for coping with the evolution of this situation is to develop or apply an enable technology such as smart manufacturing. In this article, a new trend related to manufacturing technology is presented. The cognitive agents as well as advanced ICT infrastructure increase the system robustness by avoiding centralized control and show the potential of implementing autonomous behaviors by flexible ability in decision making. The manufacturing control system based on the cognitive agents has the enough ability to adapt autonomously to disturbances without upper-level aids or a total planning modification. On the other hand, the manufacturing control system equipped with the artificial cognitive capabilities meets the requirements of flexibility, adaptability and reliability. This technology enables the applicability of cognitive behaviors of human to overcome the disturbances within the machining system. It supports the fast response to disturbances without rescheduling. In the existing manufacturing systems, the dynamic rescheduling is done when the disturbances, such as the machine breakdown or malfunction of the robot, happen. Through the applications of the smart manufacturing in practice, the productivity of the machining system and the machining quality of products will be increased by using the self-adapting and self-optimizing processes, respectively. The development of a self-evolution mechanism for solving the new possible disturbances is considered as the future work of this research.

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