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Biologically Inspired Techniques for Autonomous Shop Floor Control

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1. Introduction

Currently, the conventional manufacturing systems, such as the Flexible Manufacturing Systems (FMSs) 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 changes of the manufacturing environment, which reduce the flexibility of the systems and increase the downtime. Self-adaptation to disturbances is a crucial issue in the development of intelligent manufacturing systems, which keeps the manufacturing system running and avoids stopping completely. Many methods for the management of changes and disturbances within manufacturing systems were proposed in the literature such as rescheduling (Vieira et al., 2003; Wang et al., 2008), reactive and collaborative approaches (Monostoni et al., 1998; Leitao & Restivo, 2006). These methods can be classified by two criteria: reconfiguration and autonomy (Saadat et al. 2008). Reconfiguration is to rearrange and restructure manufacturing resources that require the rescheduling method (Vieira et al., 2003) and reconfigurable ability of manufacturing systems (Park & H.W. Choi, 2008). A dynamic rescheduling is done when there is an occurrence of disturbances such as the machine breakdown, malfunction of robot or transporter with long recovering time. Here, a new schedule is generated when the current schedule is affected by disturbances (Vieira et al., 2003; Wang et al., 2008). Autonomy allows the system to recover autonomously without modifying scheduling. Reactive and collaborative methods were proposed following this criterion (Monostoni et al., 1998). 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, the distributed control architecture is required (Park & Lee, 2000). The control architecture changes from centralized control of non-intelligent entities in hierarchical structures of the FMSs towards decentralized control of intelligent entities in distributed structures.

The new trend of the manufacturing system development is to apply autonomous behaviors inspired from biology for the manufacturing systems. Existing researches can be classified into two groups: the evolutionary algorithms based system and the manufacturing control system. In the first group, evolutionary algorithms inspired from biology such as genetic

algorithms, ant colony optimization and particle swarm intelligence are applied for the applications of Computer Aided Process Planning (CAPP) (Shan et al., 2009). In the second group, many novel paradigms that are known as intelligent manufacturing systems were proposed in the literature. The Biological, Holonic, and Cognitive manufacturing systems are the most remarkable concepts.

In the Holonic Manufacturing System (HMS), the ADACOR holonic manufacturing control architecture was proposed (Leitao, 2008). In this architecture, the manufacturing control architecture is divided into holons (Christo & Cardeira, 2007) such as the product, task, operational, and supervisor holon (Leitao & Restivo, 2006). Operational holons represent the physical resources available on the shop floor. These holons adapt to unexpected disturbances such as the machine breakdown, tool wear and so on by themselves or by the interaction with other operational holons through a supervisor holon. In this architecture, there still exists the weakness of traditional centralized and sequential manufacturing systems due to the use of the supervisor holon that reduces the flexibility of the system to respond to disturbances. This weakness will be overcome by a decentralized control architecture in which the agent technology is applied for implementing the logical part of operational holons so that these holons can directly interact among them for overcoming disturbances (D.H. Kim et al., 2009a).

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 (Ueda, 2007). 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 (Ueda et al., 2006). 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 (Zaeh et al., 2009; Nobre et al., 2008). A cognitive architecture for manufacturing systems introduced to reach this goal, is named Beliefs-Desires-Intentions (BDI) (Zhao & Son, 2008). 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 (Zaeh et al., 2009; Zhao & Son, 2008).

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. On the other hand, agent and cognitive technologies are applied separately in order to face with disturbances. The integration of these technologies brings greater efficiency for applications. BDI agents and other cognitive architectures for agents have been developed. In which agents and cognition are integrated. However, these architectures should be adjusted for specific applications in the manufacturing control field, particularly the adaptability of the manufacturing systems for unexpected disturbances.

This chapter proposes an Autonomous Shop Floor Control system (ASFrC) to adapt to internal disturbances happening on the shop floor. In the ASFrC, the resources on the shop

floor such as machine tools, robots and so on are considered as the autonomous entities. Each entity overcomes the disturbance by itself or negotiates with the others. The combination of agent and cognitive technologies for building the autonomous control entity is proposed in which the shop floor overcomes the disturbances by agent cooperation without upper level aids such as the Enterprise Resource Planning (ERP) and Manufacturing System Execution (MES). To increase autonomous operation scope of agent, the cognitive agent is proposed. Consequently, resources on the shop floor are controlled by corresponding cognitive agents. The ASFrC 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 entities in the manufacturing system with the decision making and self-controlling abilities.

The aim of this research is how the ASFrC adapts to internal disturbances (such as tool wear, machine breakdown and malfunction of robot or transporter) in a short recovering time with the non-negotiation or negotiation plan to recovery. The functionality of the proposed system was proven on the ASFrC testbed in which an ant colony inspired solution for negotiating among entities using pheromone value enables the system to overcome the disturbance in an optimal way.

2. Core technologies

2.1 Cognitive agent

The cognitive agent is a computer program which uses the beliefs-desires-intentions (BDI) architecture to arm an agent with cognitive capabilities (Zhao & Son, 2008). Beliefs are the information of the current states of an agent's environment. Desires are all the possible states of tasks that the agent could carry out. Intentions are the states of the tasks that the agent has decided to work towards. As a result, the agent performs cognitive activities that emulate the human cognitive behaviors. Cognitive activities perform a loop of three steps: perception, reasoning, and execution.

The cognitive agent inherits all characteristics from the traditional agent, including the cooperation, reactivity and pro-activeness (Toenshoff et al., 2002). The cooperation of agents is to get the global goal of the system. The reactivity is an ability of agents to respond to changes of the environment that is based on the relation between perception and action. The pro-activeness of agents is an ability to express the goal-directed behaviors. The different feature of cognitive agent in comparison with the traditional agent is intelligence shown by improving the pro-activeness characteristic. Intelligence is the ability of the agent to use its knowledge (intentions) and reasoning mechanisms for making a suitable decision with respect to the environmental changes.

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 from the environment. The decision-making module is in charge of making a decision autonomously. The control module processes the plan into tasks and executes the tasks to the environment. The interactions between the

cognitive agents are carried out via the communication module. The knowledge base module contains intentions, plans, and behavior mechanism of the agent.

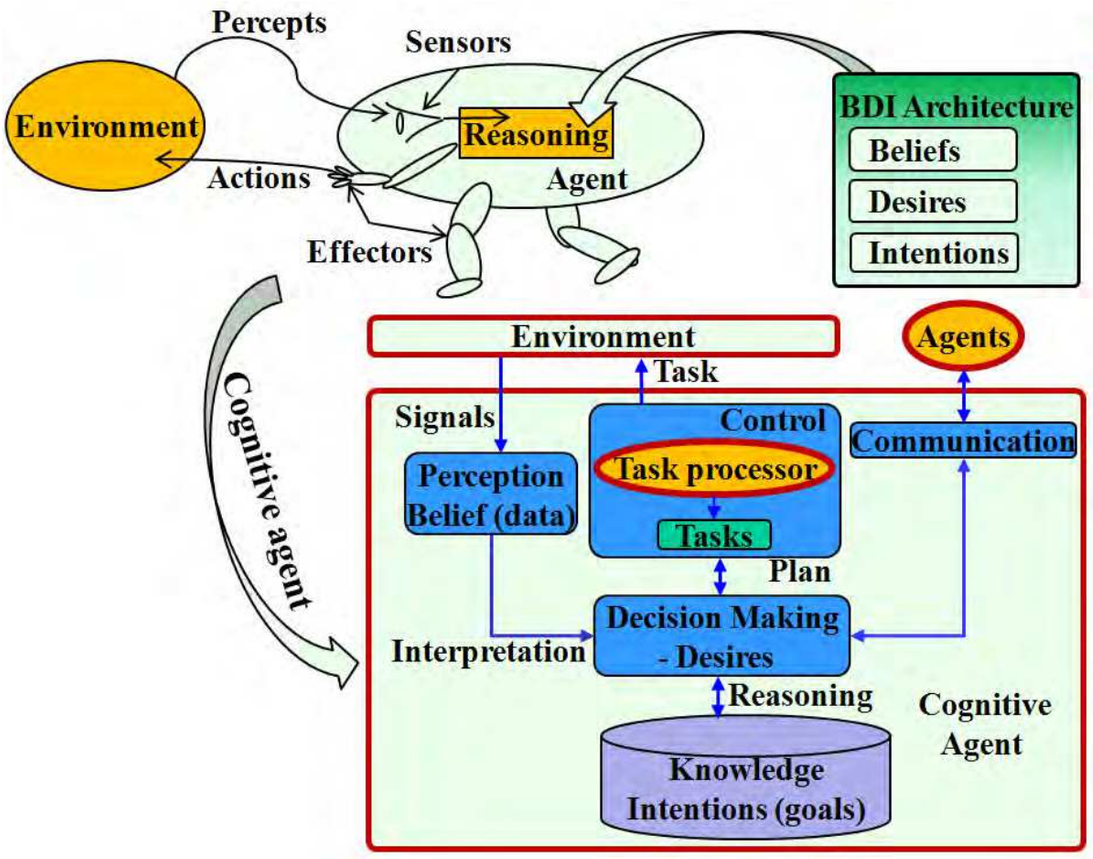


Fig. 1. Architecture of a cognitive agent

2.2 Ant colony technique

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 (Garg et al., 2009). Ant colonies show the collective intelligence as finding the shortest route from the food to their nest through the simple interactions of ants using chemical substances called pheromones as shown in Fig. 2. In order to adapt with the dynamic evolution of environment, a swarm of ants needs the self-organization ability. Self-organization is carried out by re-organizing its structure through a modification of the relationships among entities without external intervention. Transferring this principle to the manufacturing system considered as a community of autonomous and cooperative entities, the manufacturing system adapts to changes by locally matching between machine capabilities and product requirements. Each machine has a pheromone value for overcoming a specific disturbance type, and the machine with the highest pheromone value is chosen for disturbance handling (Peeters et al., 2001; Leitao, 2008).

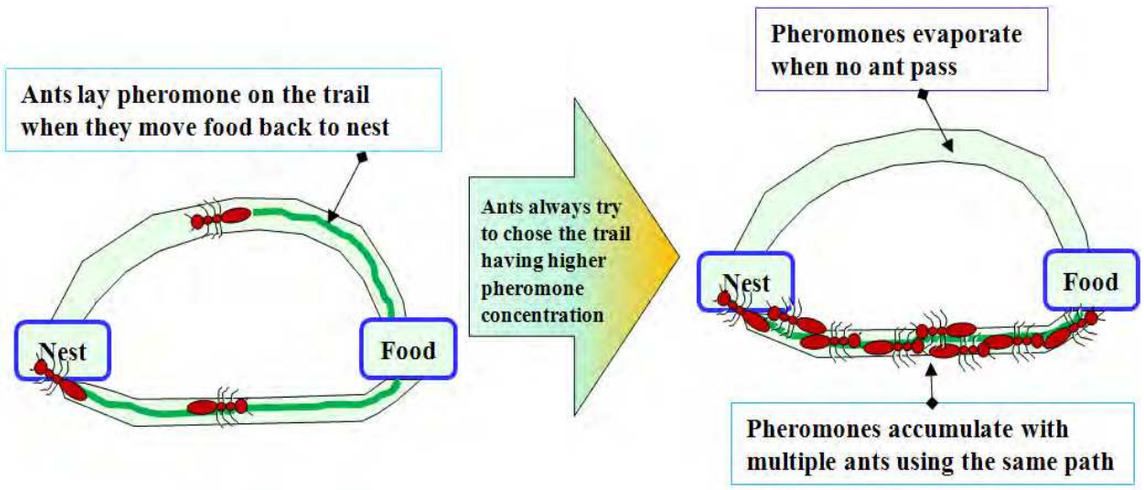


Fig. 2. The shortest route chosen by ants

2.3 ICT Infrastructure

Information and Communication Technology (ICT) infrastructure contributes significantly to the success of implementing the ASFrC. The MES provides an interface between an ERP system and shop-floor controllers due to executing functionalities such as scheduling, order release, quality control, and data acquisition (B.K. Choi & B.H. Kim, 2002). Radio Frequency Identification (RFID) technology and related sensors have a great potential in changing the way of control, production automation, and special data collection (Günther et al. 2008). They also make a contribution for cutting down labor cost, reducing breakdown time, and improving production effectiveness. Ubiquitous Sensor Network (USN) is a tool of collecting production data in real-time constraint. According to (Serrano & Fischer, 2007; M. Kim et al., 2007) the main components of an USN are the sensor network, USN access network, network infrastructure, USN middleware, and USN application platform.

In the machining system controlled by the cognitive system, RFID technology plays the role of tracking on core components in complicated processes in real time because this technology enables to read and write data to an RFID tag at the moving parts. The USN plays the role of monitoring for machine's operating status, actual production and increasing the product quality improvement (D.H. Kim et al., 2009b). The vision of "feeling" machine components is achieved by attaching multi-sensor system to these components (Denkena, 2008). Intelligent components are the results of applying sensor technologies and the ICT progress that ensure the precise operations and flexibility of the manufacturing system.

3. The manufacturing system with biologically inspired techniques

3.1 An autonomous shop floor control system

The cognitive agent based autonomous machining shop for adapting to disturbances is shown in Fig. 3. Resources on the shop floor such as machines and transporter are controlled by the corresponding agents. The workpiece agent manages the workpiece through the information stored in the RFID tag. It cooperates with the transporter agent to transfer the workpiece to the

right machine. In the normal status, the MES controls the shop floor. Otherwise, the agent overcomes the disturbance by itself or cooperates with other agents through wireless communication. In case the agents cannot solve the happened disturbance, a message is sent to the MES for rescheduling. If it takes long time to fix the occurred problems, the MES manages the whole system through communication with the ERP system. These concepts are applied to solve the internal disturbances with a short recovering time.

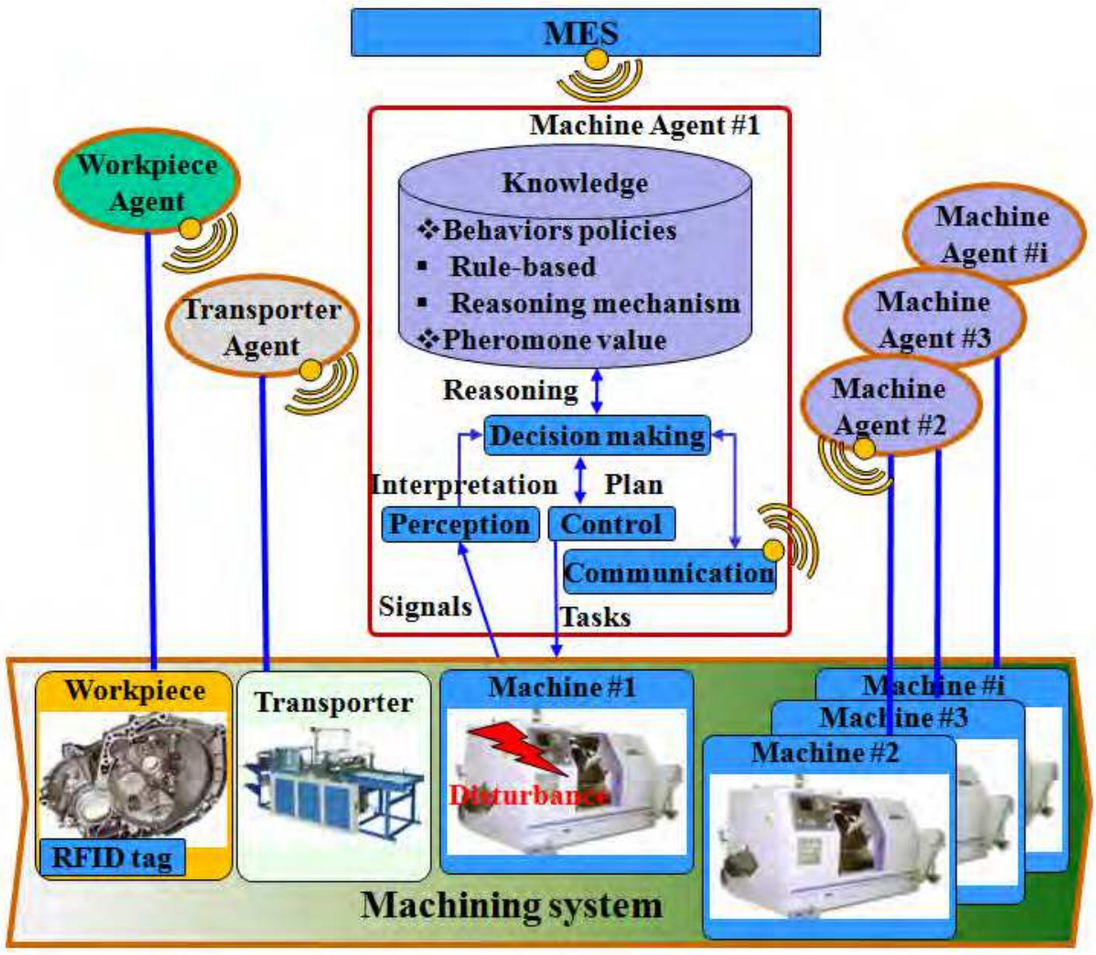


Fig. 3. Concept of an autonomous machining shop based on agents

Fig. 3 also shows the machining system for manufacturing the transmission case of the automotive company in Korea. In this machining system, the mass production method has been used. The output requirement is 300,000 parts per year. This production method requires the short cycle time such as one minute per part. Normally, the transmission case can be machined by several machines, which are the machining center with the multi-functionality. However, this method takes the long machining time. Due to the short cycle time, the operations for machining the transmission case are distributed to 17 machines on the shop floor by the MES in which one machine can carry out maximal one or two operations. To increase the flexibility of the machining system, the machining centers in the machining system are used.

There were 685 disturbances happened within the machining system during three years. From the analysis of happened disturbances, they can be classified into three groups of disturbances such as the rescheduling, non-negotiation, and negotiation group. In the consideration of taking measures, the rescheduling group means that the assigned machining task should be rescheduled due to the long recovery time, e.g. more than one hour before stopping the whole system. This time was supposed from the effect of disturbance to the planned schedule of the considered machining shop. In case that it is very hard to keep the planned schedule within the limited tolerance due to the disturbance, the rescheduling should be done by the MES. In our research, we don't consider to the rescheduling problem. We concentrate on how to remove the occurred disturbances which belong to the non-negotiation or negotiation group. The non-negotiation group consists of the disturbances of which the recovering time is less than 30 minutes and the methods for recovery are known from the previous experience. The given time for classifying non-negotiation or negotiation groups is based on the statistics of disturbances when machining transmission cases. The disturbances requiring less than 30 minutes for recovering them are mostly fixed by an operator with his own knowledge. So these disturbances were classified into the non-negotiation group. The remainder of disturbances is grouped to the negotiation type. Those disturbances can be solved with the knowledge collected when operating the conventional machining shop through the agent negotiation process within the machining shop. The disturbance analysis points out the 685 disturbances (100%) collected in the machining shop can be distributed into: the non-negotiation with 11.4%, negotiation with 40.9% and rescheduling with 47.7%. The mechanisms for adapting to disturbances that belong to non-negotiation and negotiation types are presented in Section 3.2 and 3.3.

3.2 Cognitive agent based disturbance handling

Fig. 4 shows the mechanism of the cognitive agent for overcoming the disturbance happening at the machine tool. At the beginning, both of the controllers and the cognitive agent receive the task from the MES (denoted by 1). The cognitive processor identifies the goals and transforms them into the desires. The perception module collects and filters data to obtain the information corresponding to the responsibilities of the agent. Then, the feature extraction unit categorizes the data into high and low frequencies. To diagnose the states of the machine according to the data types, the pattern recognition algorithms such as fuzzy logic or neural network are used. The cognitive agent has the reasoning process with the recognized features, desires, and intentions to make a decision. If the data obtained from the output of the perception module (denoted by 2) match 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 cognitive agent reasons the disturbance cases. If the disturbance takes a long time to recover or is unable to recover, agent sends a message to the MES to require the rescheduling (denoted by 3). Otherwise, the decision-making module generates a new plan based on the data, desires, and intentions using the neural network or rule base (denoted by 4). This plan is immediately carried out by the disturbed machine if the disturbance is easy to recover and its measure is already known (denoted by 5). For example, a tool wear is recovered by changing the cutting parameters without affecting the quality of the product. In this case, the plan is processed into tasks, and then the task command is sent to the controllers of the machine. In case the disturbance is difficult to recover. For example, if the machine breaks down, the assigned task must be executed by

another machine. The cognitive agent implements a negotiation with the other agents. The pheromone based negotiation mechanism is presented in Section 3.3. The job of the failure machine is taken over by another machine to keep the operation of the manufacturing system (denoted by 6). The agent selected through the negotiation sends a message to the workpiece agent and the transporter agent (denoted by 7) to inform them of performing the task of the failure machine. The shop floor uses the previous plan after fixing the failure machine. In case the negotiation between agents does not have any solutions, the request for rescheduling is sent to the MES (denoted by 8).

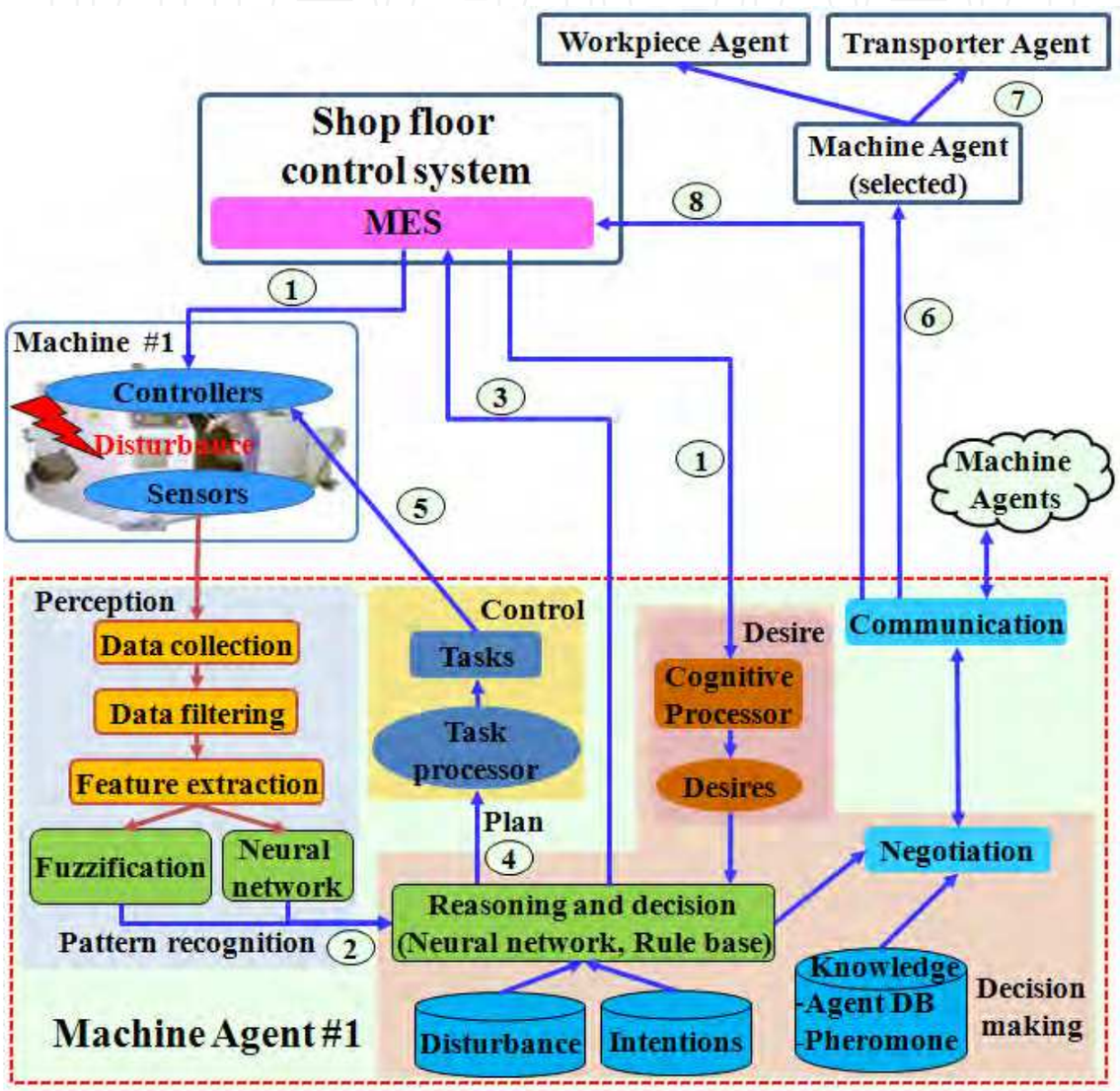


Fig. 4. Mechanism of cognitive agents for adapting to disturbances

3.3 Ant-like pheromone based agent negotiation mechanism

When the disturbance which belongs to the negotiation group happens to the machine during carrying out the operation dispatched by the MES, we need an alternative machine

to carry out that operation in order to keep the given schedule within the tolerance range. So, we consider only the disturbed operation at that time occurring the disturbance, not all operations for machining the transmission case. Due to using the machining center, there are several machines in the machining system which can carry out this operation. Therefore, we must choose a most appropriate machine among the alternative machines.

To select the most appropriate machine, the machine agent #1 managing the failure machine sends the task information to the remaining machine agents. The task information consists of the machining method, the cutting conditions, and the tool type. The machine agents compare these information to their machine ability through their database. In the database, potential factors of a machine for carrying out a task such as machine specification and capability to machine workpiece according to its functional requirements are stored. Each machine agent is considered as an ant, and the pheromone is used as a communication mediator in agent negotiation. The function of pheromone is to indicate the ability of machine for carrying out the task roughly. In agent negotiation, pheromone value is used as the criterion for choosing the optimal machine among the alternative machines. In case the machine agents meet the requirements of the task, they generate the pheromone values. Otherwise, the pheromone value equals zero.

3.3.1 Nomenclature

Q	cutting volume (mm^3)
T_t	tool life (min)
T_s	tool setup time (min)
MRR	metal removal rate of the process (mm^3/min)
v_c	cutting speed (mm/min)
f	feed rate (mm/rev)
a_p	depth of cut (mm)
k	the hourly operation cost of the machine tool ($/hour)
R_a	surface roughness of the machined part (μm)
a_{IT}	the coefficient mentions the accuracy and reliability of the machine tool affecting to the dimensional tolerance of the machined part
β	the coefficient mentions the hardness and thermal stability of the cutting tool and workpiece affecting to the form tolerance and surface integrity of the machined part

3.3.2 Pheromone value

Based on the ant colony algorithm (Xiang & Lee, 2008), the formulation for calculating the pheromone value was designed in consideration of the processing time, machining cost, and machining quality. It is shown as follows:

$$p_{MA_i} = q_t \left[\frac{1}{M_{PT} + M_c + \left(1 / M_q \right)} \right] \tag{1}$$

q_t is the executing ability of the machine MA_i about the task asked from the failure machine. If the task t can be carried out at the machine MA_i, $q_t=1$, otherwise, $q_t=0$. M_{PT}, M_c, and M_q

represent the processing time, machining cost, and machining quality of the task t at the machine MA_i, respectively. The highest pheromone value of the task requires the lowest processing time, machining cost, and the highest machining quality. After calculating the values of the M_{PT}, M_c, and M_q using equations (2), (4) and (5) respectively, these values in Eq. (1) are assumed non-dimension to calculate the pheromone value which can be used as thumb rule for assessing the machining ability of machine in terms of processing time, machining time and quality.

The same task t may have different processing times on different machines due to the different cutting parameters. These parameters are determined by the cutting conditions, machine capability and tool type. The processing time of the task t at the machine MA_i is calculated using Eq. (2). The value of the metal removal rate (MRR) of the process depends on the cutting parameters and the operation types. The value of the MRR in case of the turning operation, for example, is shown in Eq. (3).

$$M_{PT} = \frac{Q}{MRR}.(1 + \frac{T_s}{T_t}) \tag{2}$$

$$MRR = v_c.f.a_p \tag{3}$$

The machining cost factor is calculated in consideration of the hourly operation cost of the machine tool and the machining time as shown in Eq. (4).

$$M_C = \frac{k.M_{PT}}{60} \tag{4}$$

In the machining quality, the functional requirements of workpiece such as dimension, tolerance, surface roughness and micro structural change must be fulfilled. The machining quality factor was considered in the relationship between the machine specifications, cutting tool, and material properties (Toenshoff et al., 2000). It was empirically evaluated for the quantification in consideration of the allowed limitations of cutting condition, the machining ability of a machine in terms of accuracy and reliability as well as the hardness and thermal stability of the cutting tool and workpiece. The formula for quantifying the machining quality is given as follows:

$$M_q = \frac{1}{R_a.\alpha_{IT}.\beta} \tag{5}$$

The surface roughness of the machined part is calculated using the theoretical formula (Eq. (6)) (Cus & Zuperl, 2006).

$$R_a = p.v_c^{x1}.f^{x2}.a_p^{x3} \tag{6}$$

where $x1$, $x2$, $x3$, and p are the constants relative to the combination of tool and workpiece, which are given in the machining handbooks. The values of v_c, f, and a_p are in the allowed limitations of cutting condition of the machine tool.

The machines in terms of the accuracy and reliability can be classified into the precision machine and the high precision machine. The dimensional tolerance of the machined part is

in the range of IT6÷IT7, IT3÷IT5 using the precision machine, and the high precision machine, respectively. The a_{IT} coefficient was determined as follows:

Machine	Precision	High precision
International Tolerance (IT) quality	IT6÷IT7	IT3÷IT5
a_{IT}	1	0.5

Table 1. The value of a_{IT}.

The objective of any machining operation is to maximize the *MRR* after the fulfillment of all required quality conditions. The machining method in terms of the *MRR* can be classified into the conventional machining and the high speed machining. The *MRR* of the high speed machining is 5÷10 times higher than of which of the conventional machining. However, the higher *MRR* will result in the higher thermal damage on the workpiece and cutting tool which affects to the machining quality of the machined part. The differences in dimensional accuracy of the machined part are caused by the thermal expansion of tool and workpiece. In particular, with the same machining conditions thermal expansion on the tool tip and workpiece can reach up to 10 and 15 μm, respectively (Zhou et al., 2004). The experimental results reported in the literature show that the use of cooling lubricants increases the workpiece quality and prevents the form errors due to thermal effects (Toenshoff et al., 2000). Assuming that the contribution of thermal effects to the overall error of the machined parts is more than 50%, and the *MRR* of the conventional machining calculated in consideration of the optimal cutting parameters (v_c, f, and a_p) is known. So the *MRR* of the high speed machining is in the range of (5÷10) *MRR*. Based on the machining methods (conventional machining or high speed machining) and the cooling method (using coolant or dry machining), the value of the β coefficient was given in Table 2 and Table 3.

Method	β
Conventional machining and using coolant	0.5
Conventional machining and dry machining	0.6

Table 2. The value of β in the case of the conventional machining.

Method		β
High speed and using coolant		0.5
High speed and dry machining	5.*MRR*	0.6
	6.*MRR*	0.7
	7.*MRR*	0.8
	8.*MRR*	0.9
	9.*MRR*	1.0
	10.*MRR*	1.1

Table 3. The value of β in the case of the high speed machining.

3.3.3 Pheromone based agent negotiation

According to the generated pheromone values of the task *t* at the different machines, the machine agent #1 uses the algorithm given as follows for making a decision.

Case 1: All pheromone values are zero.
send (message) /*requesting the MES for rescheduling*/
Case 2: There is only one the pheromone value of the machine agent (i) that is not zero.
send (message) /* the machine agent (i) is selected*/
Case 3: There are more than two pheromone values that are not zero.
If the machine agent (j) has the highest pheromone value
send (message) /*the machine agent (j) is selected*/

The algorithm for the remaining machine agents in the negotiation process is given as follows:

analyse (message) /*matching the content of task information with their ability*/
generate (pheromone) /*generating the pheromone value of the assigned task*/

4. Implementation

The cognitive agents were developed using the .NET platform and C#. The system architecture of the ant colony inspired machining shop is shown in Fig. 5. 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 the RFID reader, disturbance input, and alarm device. 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™ 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.

4.1 Reaction of the system in the case of non-negotiation

Fig.6 illustrates the non-negotiation process of the ASFrC. At the beginning, the MES system dispatches the jobs to the corresponding machines based on the machine agent ID. The normal status of the machine is shown by the green light. The disturbance occurs at the machine #1 that is shown by turning "ON" of the disturbance generator. The red light is "ON" and the alarm is shown on the display screen. The machine agent #1 gets the disturbance signal through the PLC #1. It diagnoses the disturbance type based on its disturbance database. If the disturbance belongs to the non-negotiation type; for example, the tool wear, the agent adjusts the cutting parameters, which are determined by using the

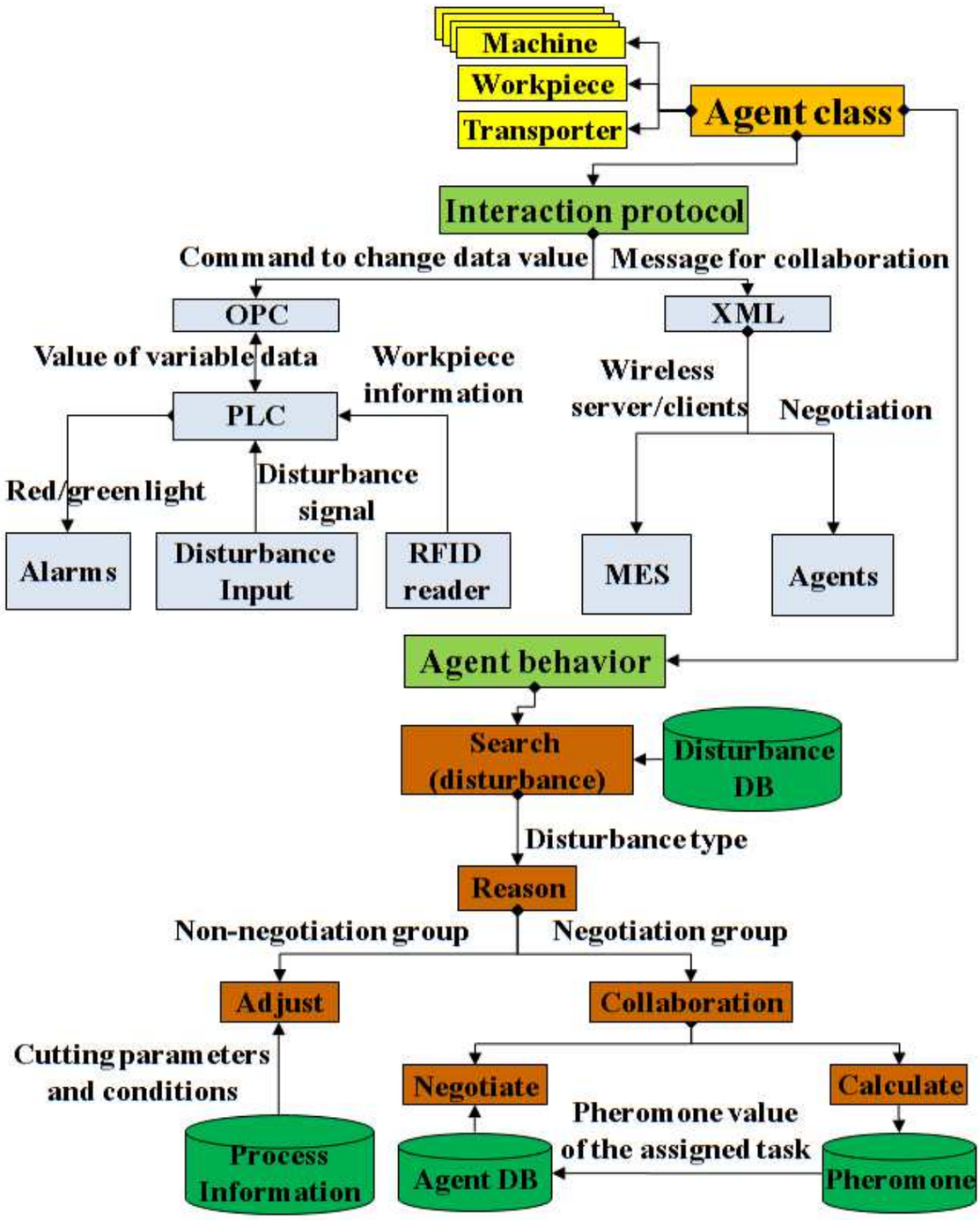


Fig. 5. System architecture of the ant colony inspired machining shop

neural network with the inputs such as the existing cutting parameters and conditions, tool information. In case the new parameters are generated, the machine runs the operation continuously and the green light is "ON". Otherwise, the disturbance is considered as the negotiation type, and the agent activates the negotiation with other agents.

The screen shot of the developed system in the case of tool wear is shown in Fig. 7. The machine agent #1 gets the disturbance signal from the PLC #1 through KEPServerEx™ software (denoted by 1). It analyses the disturbance type based on its disturbance database (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 determined by using the neural network. After changing the parameters newly (denoted by 4), the machine agent sends these parameters to the controller of the machine.

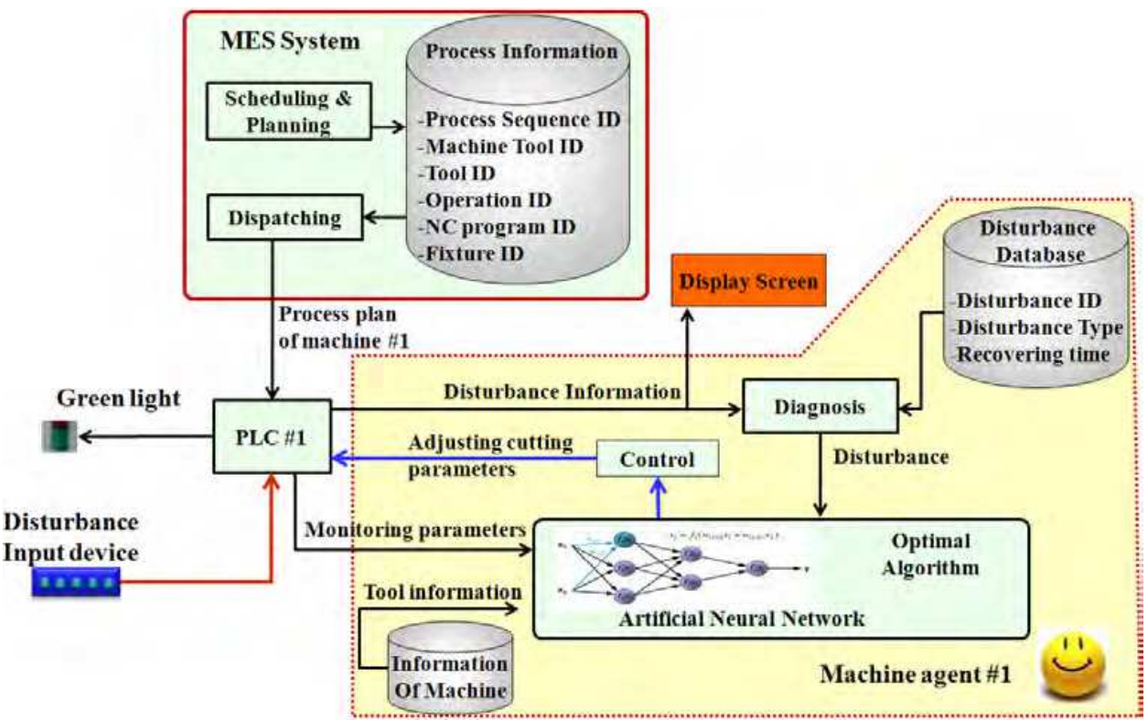


Fig. 6. Non-negotiation process of the ASFrC



Fig. 7. The screen shot of the system in the case of tool wear

4.2 Reaction of the system in the case of negotiation

Assuming that the disturbance happens on the machine #1, and the agent diagnoses it belongs to the negotiation group, for example, tool-broken. Immediately, the negotiation of machine agents is activated as shown in Fig. 8. The machine agent #1 sends a message for help to the remaining machine agents. This message consists of the machining information and addresses of the receiving machine agents. The machine agents negotiate to find out another route. This negotiation is based on the evaluation of the pheromone values of machine agents, the precedence relationship between the operations, and current status of the machines. Each machine has a pheromone value for a specific operation and the machine with the shortest processing time, lowest machining cost and highest machining quality for a specific operation has the highest pheromone. After negotiating, the machine agent #2 is chosen for machining the task #1 of the machine #1. The machine agent #2 cooperates with the transporter and workpiece agent to carry out the accepted job. As the result, the green light at the machine #2 is "ON".

The screen shot of the developed system in the case of tool broken is shown in Fig. 9. The disturbance belongs to the negotiation type (denoted by 3). The network of server/clients is established for agent negotiation (denoted by 4). Then, the negotiation of machine agents is

activated using the ant colony based mechanism presented in Section 3.3 (denoted by 5). After negotiating, the machine agent with the highest pheromone value is chosen for carrying out the task #1 of the machine #1.

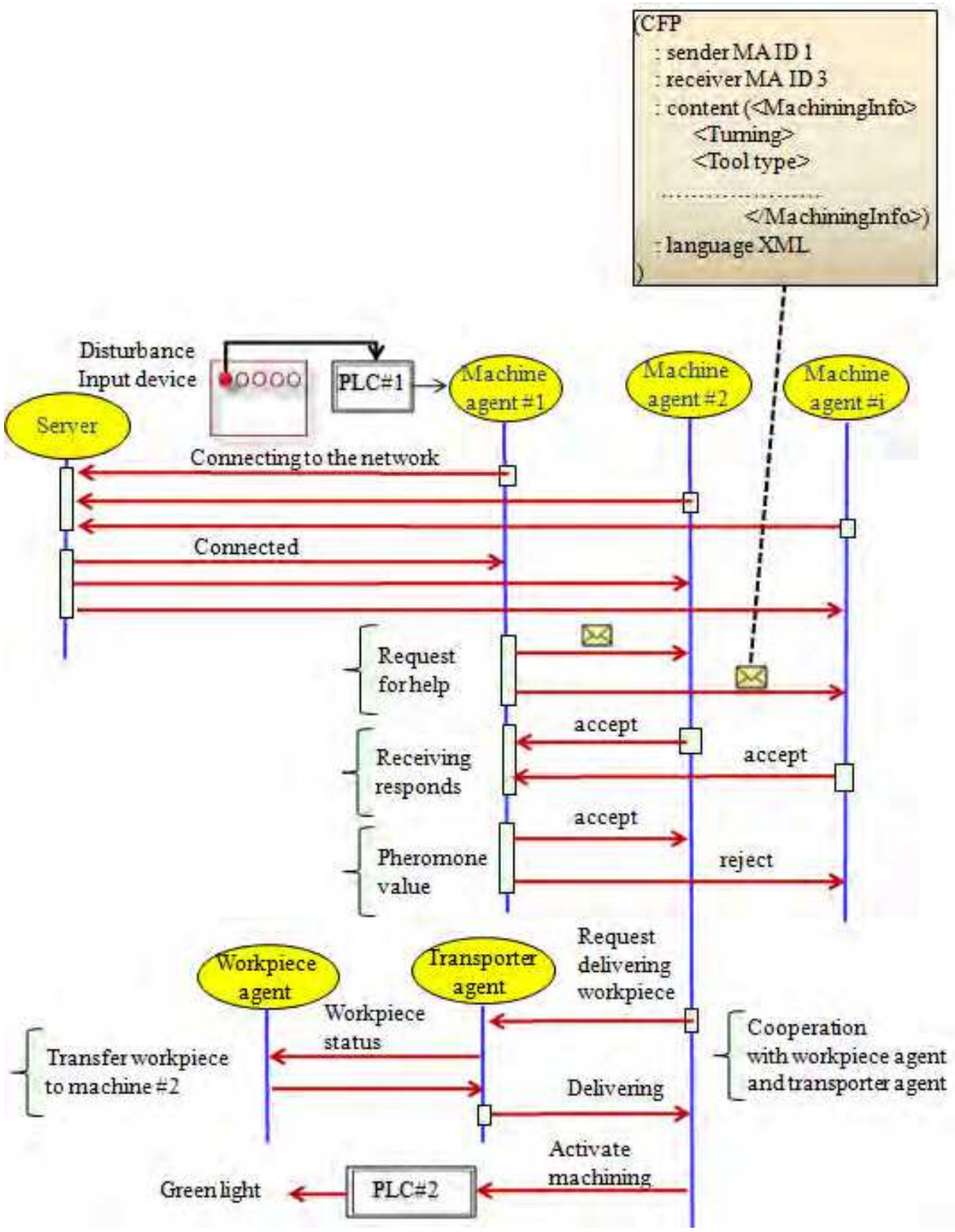


Fig. 8. Negotiation process of the ASFrC

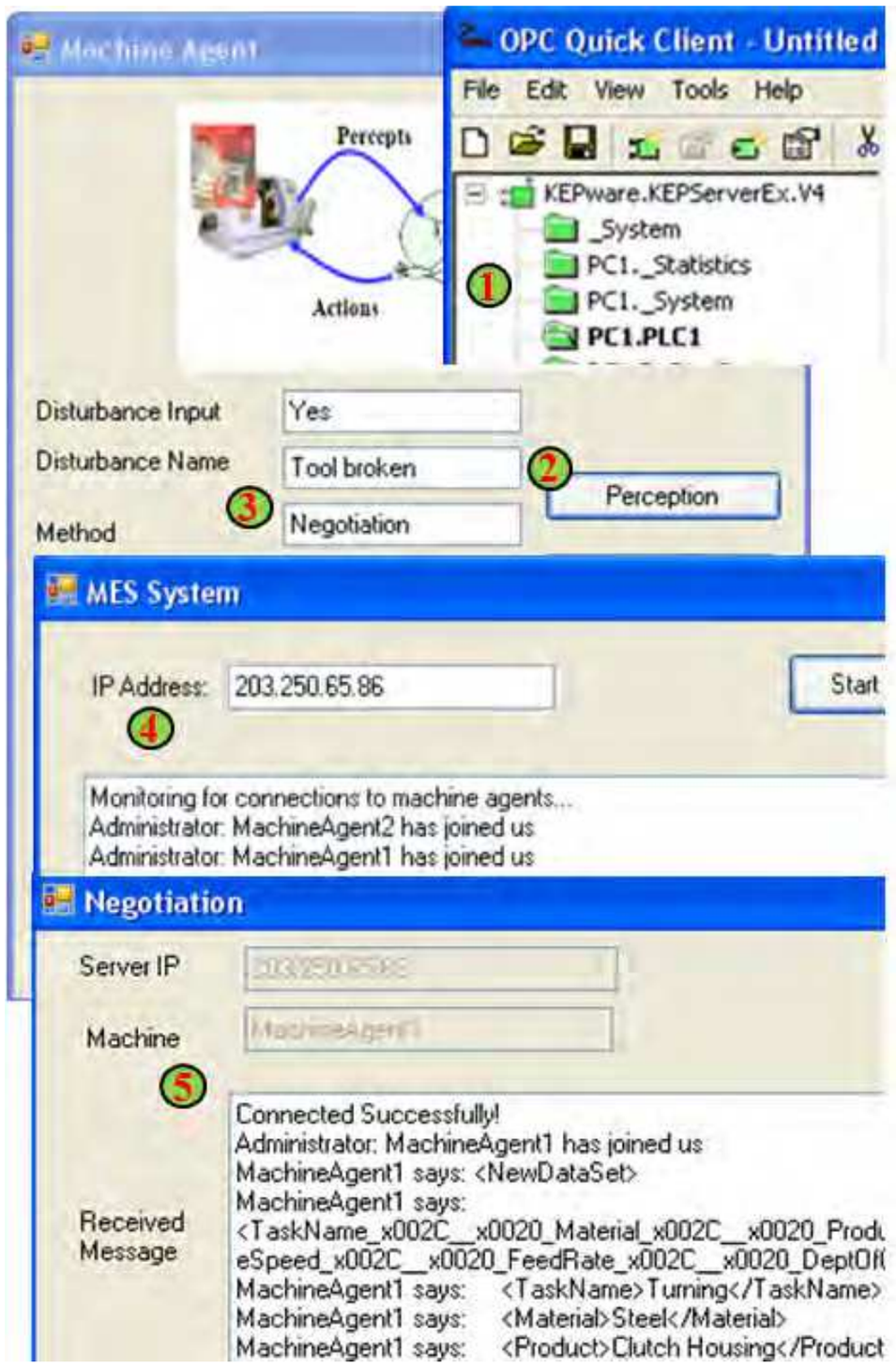


Fig. 9. The screen shot of the system in the case of tool broken

4.3 Experimental results

The functionality of the developed system was proven on the ASFrC testbed shown in Fig. 10. The disturbance generators (turn on/off switches) are used to generate disturbances. The PLCs considered as the controllers of the machine tools get the processing information from the MES and execute the machining jobs. The processing information of the system is displayed on the monitoring screen. The workpiece information is collected by the RFID system. The cognitive agents representing the machines, workpiece, and transporter are installed on the personal computers (PCs). Through the collaboration of each PC, the machining process of a workpiece is executed completely. The experimental results show that the developed system overcomes the disturbances successfully which belong to the non-negotiation or negotiation type. Through that, the manufacturing productivity is increased.

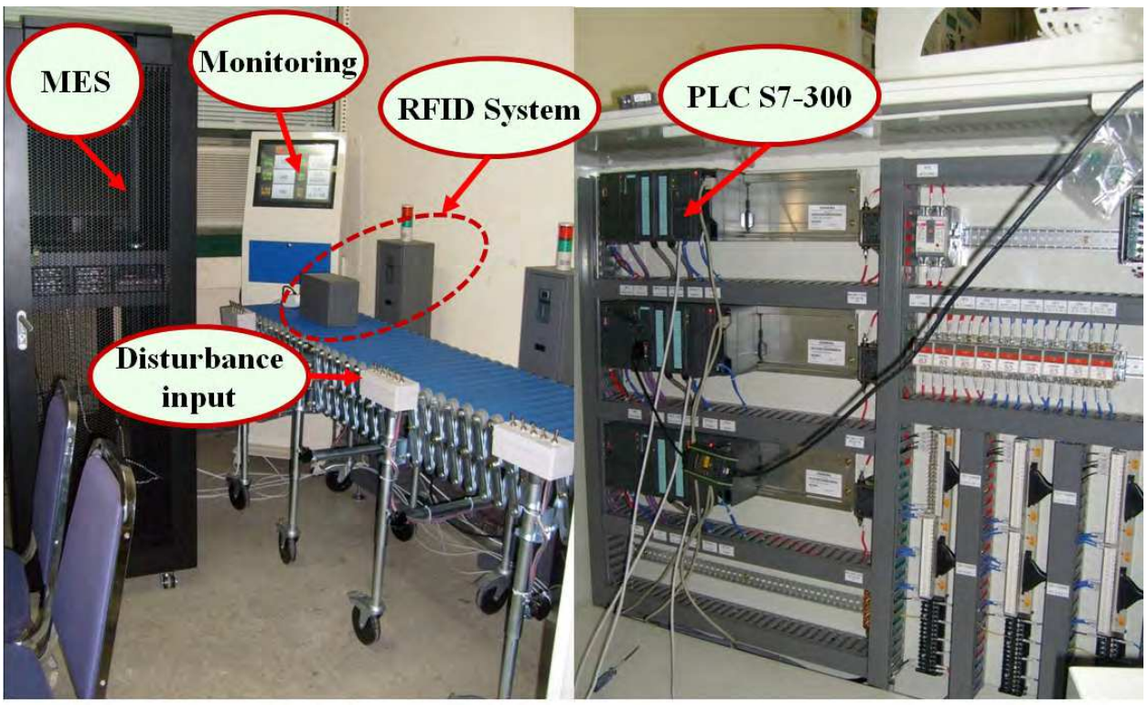


Fig. 10. Experimental setup

5. Conclusion

The Autonomous Shop Floor Control system (ASFrC) with biologically inspired techniques is a feasible solution for adapting autonomously to disturbances. It meets the requirements of flexibility, adaptability, and reliability. This research also proved the efficiency of applying the biologically inspired technologies such as cognitive agent and ant colony technique into the manufacturing field. These technologies are necessary for the future manufacturing systems.

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The book "New Technologies - Trends, Innovations and Research" presents contributions made by researchers from the entire world and from some modern fields of technology, serving as a valuable tool for scientists, researchers, graduate students and professionals. Some practical applications in particular areas are presented, offering the capability to solve problems resulted from economic needs and to perform specific functions. The book will make possible for scientists and engineers to get familiar with the ideas from researchers from some modern fields of activity. It will provide interesting examples of practical applications of knowledge, assist in the designing process, as well as bring changes to their research areas. A collection of techniques, that combine scientific resources, is provided to make necessary products with the desired quality criteria. Strong mathematical and scientific concepts were used in the applications. They meet the requirements of utility, usability and safety. Technological applications presented in the book have appropriate functions and they may be exploited with competitive advantages. The book has 17 chapters, covering the following subjects: manufacturing technologies, nanotechnologies, robotics, telecommunications, physics, dental medical technologies, smart homes, speech technologies, agriculture technologies and management.

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