Applications of Collective Behavior Concepts in Flexible Manufacturing Systems

SZABÓ Loránd[1], KÁPTALAN Erna[2], SZÁSZ Csaba[3]

[1] Technical University of Cluj, Department of Electrical Machines
28 Memorandumului str., 400114 Cluj, Romania
e-mail: Lorand.Szabo@mae.utcluj.ro

[2] Babeş-Bolyai University, Department of Physics
1 Kogâlniceanu str., 400084 Cluj, Romania
e-mail: kaptalane@yahoo.com

[3] Technical University of Cluj, Department of Electrical Drives and Robots
28 Memorandumului str., 400114 Cluj, Romania
e-mail: Csaba.Szasz@edr.utcluj.ro

***Abstract* – Global competition and rapidly changing customer requirements are forcing major changes in advanced fabrication systems. Nowadays multi-agent technologies are considered as an important approach for working out highly developed flexible manufacturing systems. Nature is suitable sources of inspiration for this, since it can help researchers to achieve better solutions for self-adaptive and evolvable complex manufacturing systems. The present paper is a survey on diverse applications of collective behavior concepts in this field: multi-agents systems, holonic manufacturing systems, swarm robotics, etc.**

***Keywords*: flexible manufacturing systems, multi-agent systems, holonic manufacturing systems, swarm robotics.**

I. INTRODUCTION

Modern manufacturing is characterized by low-volume, high-variety production and close-tolerance, high-quality products. In response to the ever-increasing competition in the global market, major efforts have been devoted to the research and development of various technologies to improve productivity and quality. The economic pressure for increasing quality, productivity, and efficiency of manufacturing processes has motivated the development of more complex and intelligent flexible manufacturing systems [1].

Aiming to address the emergent requirements imposed to the fabrication domain, a current challenge to design re-configurable and responsiveness manufacturing systems is to consider multi-agent and holonic designs by combining them with the insights offered by biological inspired techniques, as swarm intelligence and self-organization.

By understanding how in nature the complex things are performed in a simple and effective way the researchers working in these fields may copy and develop complex and powerful adaptive and evolvable systems. Additionally, these concepts can be combined with insights from emergent theories from computer science, namely the artificial life and evolutionary computing [2].

II. THE MAIN REQUIREMENTS FOR ADVANCED FLEXIBLE MANUFACTURING SYSTEMS

Nowadays the traditional centralized and sequential manufacturing planning, scheduling, and control mechanisms are being found insufficiently flexible to respond to changing production styles and highly dynamic variations in product requirements [3].

Unfortunately, the traditional production approaches imposes a limit on the expandability and reconfiguration capabilities of the manufacturing systems. The traditional, centralized and hierarchical manufacturing organization is also very sensible to shut downs due to failures.

Agent technology provides a natural way to overcome such problems, and to design and implement advanced distributed and intelligent manufacturing systems [4].

Presently tremendous researches are carried out to apply agent based technology for advanced manufacturing enterprise integration, supply chain management, manufacturing planning, scheduling and control, materials handling, respectively to holonic manufacturing systems [5]. A detailed review on the main applications of agent-based systems in intelligent manufacturing systems is given in [6].

Manufacturing enterprises in our century must be high-tech environments where markets are frequently shifting, new technologies are continuously emerging, and competitors are multiplying globally. Therefore manufacturing strategies must shift to support global competitiveness, new product innovation and introduction and rapid market responsiveness.

The next generation manufacturing systems will thus be more strongly time-oriented, while still focusing on cost and quality. Such systems will need to satisfy the following fundamental requirements [4]:

i.) *enterprise integration*: the manufacturing system has to be integrated with its related management systems and its partners via networks.

ii.) *distributed organization*: distributed knowledge-based systems are required to link demand management directly to resources and capacity planning and scheduling.

iii.) *heterogeneous environments*: the demand of using heterogeneous software and hardware in both the manufacturing and its information system.

iv.) *interoperability*: the heterogeneous software environments must interoperate efficiently.

v.) *open and dynamic structure*: it must be possible to dynamically integrate new subsystems (software, hardware, or manufacturing devices) into, or remove existing subsystems from the system without stopping and reinitializing the working environment.

vi.) *cooperation*: the requirement of full cooperation with suppliers, partners, and customers.

vii.) *integration of humans with software and hardware*: people and computers must be integrated to work collectively with rapid access to required knowledge and information. Efficient communication tools are required to allow effective, quick communication between humans and computers.

viii.) *agility*: the product cycle time must be reduced in order to be able to respond to customer desires quickly. The manufacturing system must be quickly adapted to the continuous and unanticipated changes. Therefore the manufacturing facilities must be able to rapidly reconfigure and interact with heterogeneous systems and partners.

ix.) *scalability*: the possibility that additional resources be incorporated into the organization as required.

x.) *fault tolerance*: this means that the manufacturing system must be fault tolerant at all levels. It must be able to detect and recover from system failures and minimize their impacts on the working environment.

These requirements can be fulfilled only by applying *artificial intelligence* (AI) in intelligent manufacturing systems. The recent developments in *multi-agent systems* in the new domain of *distributed artificial intelligence* (DAI) promise new and interesting possibilities in improving manufacturing systems [7].

III. MULTI-AGENT SYSTEMS

The *agents* are on the basis of several advanced manufacturing systems. An agent is basically a system with powerful computational skills placed in a dynamic environment. It is capable of exhibiting autonomous and intelligent behavior.

An agent operates in an environment from which it is clearly separated, as shown in Fig. 1. An agent can make observations about its environment, has its individual knowledge and beliefs about its environment, has preferences regarding the states of the environment, and can initiate and execute diverse actions to change the environment [8], [9].

Fig. 1. The agent and its environment [8]

An agent may be in an environment that includes other agents. The community of interacting agents forms a higher leveled unit, a *multi-agent system*.

Multi-agent systems offer a way to relax the constraints of centralized, planned, sequential control in manufacturing systems. They offer advanced production systems that are decentralized rather than centralized, emergent rather than planned, and concurrent rather than sequential.

The *autonomous agent* approach replaces a centralized database and control computer with a network of agents, each endowed with a local view of its environment, respectively the ability and authority to respond locally to that environment. The overall system performance is not globally planned, but emerges through the dynamic interaction of the agents in real-time. Thus the system does not alternate between cycles of scheduling and execution. Rather the schedule emerges from the concurrent independent decisions of the local agents [10].

Autonomous agent systems are inspired by models from biology (ecosystems) and economics (markets), in contrast with the military patterns of hierarchical organization manifested by traditional approaches.

As each agent is close to the point of contact with the real world, the system's computational state tracks the state of the world very closely, without need for a centralized database. This is the main advantage of such systems. Since overall system behavior emerges from local decisions, the system readjusts itself automatically to environmental noise or the removal or addition of agents. The software for each agent is much shorter and simpler than would be required for a centralized approach, and as a result is easier to write, debug, and maintain [10].

The functions that must be ensured by the multi-agent system are the following [11]:

i.) those of the agents (interactions between the agents and the environment, respectively the other agents, with respect to the imposed organization)
ii.) those resulted from the added value generated by the agents evolving in a multi-agent world, which are usually encompassed under the name *collective intelligence*.

The main research topics in this field are related to the following fields [12]:

i.) cellular (reconfigurable) manufacturing robotic systems;
ii.) multi robot motion planning;
iii.) architectures for multi-robot cooperation.

The most important issues to be studied in multi-robot systems are [12]:

i.) communication in the multi-robot team;
ii.) architectures, task planning and control;
iii.) localization, mapping and exploration;
iv.) object transport and manipulation;
v.) motion coordination;
vi.) reconfigurable robotics,
vii.) learning;
viii.) biological inspirations.

Nearly all of the work in *cooperative mobile robotics* began after the introduction of the new robotics paradigm of *behavior-based control*. Since this paradigm is rooted in *biological inspirations,* in the frame of the cooperative robotics research the social characteristics of insects and animals must be examined and applied. The most common applications of this knowledge are in the use of the simple local control rules of various biological societies (ants, bees, and birds) in cooperative robot systems [12].

The main advantage of *self-organization* of the autonomous robots through a process based on *artificial evolution* is that it is an ideal framework for synthesizing robots whose behavior emerges from a large number of interactions among their constituent parts. This can be explained by considering that, in evolutionary experiments, robots are synthesized through a self-organization process based on random variation and selective reproduction, where the selection process is based on the behaviors that emerge from the interactions among the robot's constituent elements and between these elements and the environment. This allows the evolutionary process to freely exploit interactions without the need to understand the relation between interactions and emergence.

On the basis of the same argument it can be assumed that the evolutionary approach can be successfully applied also to synthesize robots able to display *collective behavior*. In this case evolving individuals might exploit not only the properties that emerge from the interactions among the constituent elements of the robot and between the robot and the environment, but also the interactions among different individual robots [13].

Hence multi-agent systems are more and more used in numerous industrial applications, as manufacturing control, logistics and production planning [14].

IV. THE HOLONIC MANUFACTURING SYSTEMS

Industries with mass-production of individually customized products, like automotive, aerospace industries, are characterized by highly variable customization requirements, changes in technology and frequently the changes of plans due to the used equipment. Such requirements and emergency situations can be conveniently and flexibly handled by the multi-agent technology.

A specific class of multi-agent systems, the *holonic system*, is one of the best choices for such purposes since they are using the concept of agents' reactivity and are able to perform system reconfiguration in order to achieve pre-programmed situations [14].

Holonic manufacturing was first proposed as a new manufacturing paradigm in the beginning of the 90's and since then it received a lot of attention both in academic and industrial researches [15]. It can be used to combine hierarchical organizational structure with decentralized control [16].

The "*holon*" term was originally coined by A. Koestler basing it on the Greek word "*holos*" for "*whole*" and the suffix "*-on*" that denotes "*part*". A holon is stable, coherent and it consists of several holons as sub-structures, and itself can be part of a greater whole. None of these components can be understood completely without their sub-components, or without the super-component they are part of.

The holons can form diverse configurations:

i.) A holon can b e considered as an autonomous agent. It can be assumed that the subholons are fully autonomous agents with predefined architecture. A superholon formed of several subholons is a new conceptual entity whose properties are made up by the properties of the original subholons.
ii.) Several agents can merge into one superholon. In this case the merging agents completely give up their autonomy, but they may be re-invoked when the superholon is terminated.
iii.) The above two solutions are extremes and they are only useful in very specific circumstances. In a hybrid way of forming a holon the agents give up only a part of their autonomy. A single head (the superholon) is allowed in the system, the rest of the agents remain the population. The competence of the superholon may range from purely administrative tasks to the authority to give directives to other subholons. Furthermore, the head may have the authority to plan and negotiate for the holon on the basis of its subholons' plans and goals, and even to

remove some subholons, or to incorporate new subholons [17].

The holonic systems are able to self-organize by altering the holonic hierarchy following perturbations of the agent environment using diverse decision making techniques (for example fuzzy-evolutionary reasoning) [18].

Practically a *holonic manufacturing system* (HMS) consists of autonomous, self-reliant manufacturing units, called holons. Any unit, like a machine, a robot, a conveyor belt, a work piece, or an order can be a holon, as long as the unit is able to create and control the execution of its own plans and/or strategies [19].

In this case a holon always contains an information processing part and optionally a physical processing part. Holons cooperate with other holons during the production process in order to accomplish the production objectives.

V. SWARM ROBOTICS

In flexible manufacturing systems the motion (trajectory) planning of the mobile robots is a very important issue [20], [21].

In the early age of robotics only one mobile robot was considered in motion planning. The single robot required some measures to be performed in order to find the target without collision with obstacles while meeting several predefined conditions. Its efficiency was low, since it was difficult to find the target rapidly and execute his tasks since the information obtained by it was very limited. Furthermore, if this single robot was damaged, the task completely failed.

Swarm robotics is a novel approach to the coordination of large numbers of relatively simple robots, which takes its inspiration from social insects (ants, wasps or termites), as shown in Fig. 2 [22].

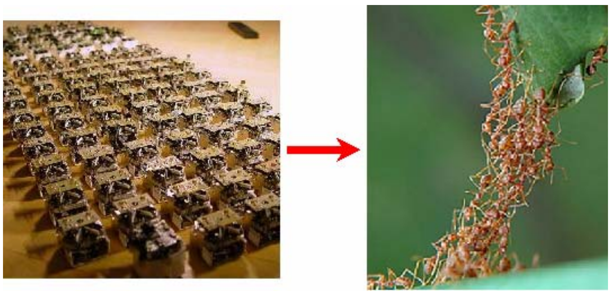

Fig. 2. The principle of swarm robotics

These insects can coordinate their behaviors to accomplish tasks that are beyond the capabilities of a single individual.

Ants can carry large preys to their nest; termites can build large mounds from mud, etc. The emergence of such synchronized behavior at the system level is a source of inspiration for researchers working in the field of multi-agent robotic systems [23].

The system-level operation of a swarm robotic system should exhibit three functional properties that are observed also in the nature:

i.) *Robustness*: the system should be able to operate despite disturbances from the environment or the malfunction of its individuals. Swarms are inherently redundant systems since the loss of an individual can be immediately compensated by another one. Their coordination is decentralized and therefore the destruction of a particular part of the swarm will not stop its operation. The individuals that make up the swarm are relatively simple, making them less prone to failure.

ii.) *Flexibility*: the individuals of a swarm are able to coordinate their behaviors to tackle tasks of different nature (the ants can collectively find the shortest path to a food source).

iii.) *Scalability*: the swarm should be able to operate under a wide range of group sizes and support a large number of individuals without decreasing the performance considerably. Therefore the coordination mechanisms and strategies to be developed for swarm robotic systems should ensure the operation of the swarm under varying swarm sizes [23], [24].

The main requirements for the swarm robotic system are:

i.) *Optimized coordination* between the individual which must interact with their environment.

ii.) The individual robots must be *homogeneous*, near identical, at least at the level of interactions.

iii.) They must be *simple*, as concerning the limitations in their individual capabilities relative to the task, and not the hardware and software complexity of the robots.

iv.) The individuals should have *local interaction abilities*, which ensure that the coordination between the robots is distributed, and that it is more likely to scale with the size of the swarm [23], [25].

The key issue in swarm robotics is the *coordination* mechanisms between the individual robots. Studies in physical and biological systems revealed that there are several coordination mechanisms known in nature which can act as sources of inspiration for coordinating swarm robotic systems.

The most important two such coordination mechanisms are self-organization and stigmergy.

Self-organization is by definition a process in which patterns at the global level of a system emerge solely from numerous interactions among the lower level components of the system [26]. Interplay of positive and negative feedback of local interactions among the individuals is essential. Positive feedback is typically generated through autocatalytic behaviors, as execution of a behavior increases the triggering of the very same behavior. Such a positive feedback cycle is then counterbalanced by a negative feedback mechanism.

Stigmergy is defined as indirect communication of individuals through environment [27]. Stigmergic communication is common between many social insects. For example ants are known to lay pheromones on the ground to mark the paths to food sources, and these pheromones act as attractants to be followed by ants [23].

During the last years an increased interest in swarm robotics can be observed. This growing interest is mainly catalyzed by the significant advances in mechatronics, which made possible to shrink the size and the cost of robots for mass production [28].

The perspective to use swarm robots can be seen in many applications. They can avoid human intervention in some high risk environments, such as fire fighting, landmine detection, or finding survivors after an earthquake. Utilizing swarm robots, it is not necessary to worry about failure caused by a few damaged robots [29].

A large number of international projects have been conducted in this field and others are in progress [30]. Next the most significant projects are presented.

The *SWARM-BOTS* are autonomous mobile robots with self-assembling capabilities. They take advantage from collective and distributed approaches to ensure robustness to failures and to hard environment conditions in tasks such as navigation, search and transportation in rough terrain. One SWARM-BOT is composed of a number of simpler, physically interconnected robots, called *s-bots*, (see Fig. 3). The SWARM-BOT is provided with self-assembling and self-reconfiguring capabilities, whereby s-bots can connect and disconnect forming large flexible structures [31], [32].

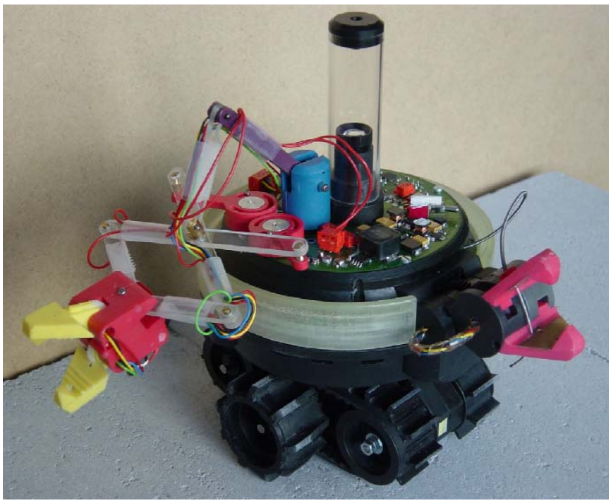

Fig. 3. An s-bot's prototype [31]

SWARMANOID is a continuation of the SWARM-BOTS project having the main goal to build heterogeneous swarms that can act also in three-dimensional space. Three types of s-bots were included in the project: eye-bots, hand-bots (see Fig. 4) and foot-bots [33].

The *SYMBARION* (*Symbiotic Evolutionary Robot Organisms)* project had the main objective to investigate and develop novel principles of adaptation and evolution for symbiotic multi-robotic "organisms" based on

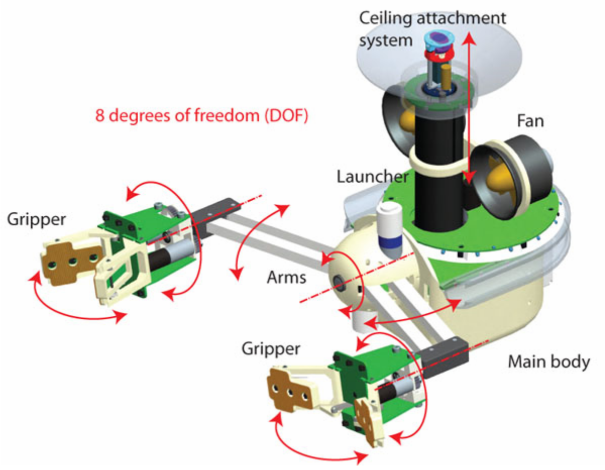

Fig. 4. A hand-bot built up in the frame of the SWARMANOID project [34]

biomimetic approaches and modern computing paradigms. These organisms consist of large-scale robot swarms which can dock with each-other and symbiotically share energy and computational resources, as well as autonomously managing their own hardware and software. This way they can self-configure, self-heal, self-optimize and self-protect. These properties will make them very adaptable, evolvable and scalable. They will also be able to re-program themselves without direct human supervision, to develop their own cognitive structures and to allow new functionality to emerge [30].

As it could be seen the swarm does not simply mean only adding some individual robots together. The behavior shown by the swarm robots should be collective, coordinated and requires information exchange. So far, many methods and algorithms are used for the motion planning of swarm mobile robots, including traditional and recursive biology inspired methods.

VI. CONCLUSIONS

As nature is believed to be "perfect", researchers working to improve manufacturing systems should make use of the marvelous world of social insects that are able to form natural decentralized control systems. Several examples of collective behavior in nature can motivate the control of multiple robot systems by using group behavior techniques.

REFERENCES

[1] W. Jacak, *Intelligent robotic systems: design, planning, and control*: Springer US, 1999.

[2] P. Leitao, "Holonic Rationale and Bio-inspiration on Design of Complex Emergent and Evolvable Systems," *Transactions on Large-Scale Data-and Knowledge-Centered Systems I,* pp. 243-266, 2009.

[3] H. Shivanand, *Flexible Manufacturing System*. New Delhi (India): New Age International, 2006.

[4] S. Weiming, *et al.*, "Agent-based distributed manufacturing process planning and scheduling: a state-

of-the-art survey," *IEEE Transactions on Systems, Man and Cybernetics, Part C: Applications and Reviews,* vol. 36, pp. 563-577, 2006.

[5] D.C. McFarlane and S. Bussmann, "Developments in holonic production planning and control," *Production Planning and Control,* vol. 11, pp. 522-536, 2000.

[6] W. Shen and D.H. Norrie, "Agent-based systems for intelligent manufacturing: A state-of-the-art survey," *International Journal of Knowledge and Information Systems,* vol. 1, pp. 129-156, 1999.

[7] G. Weiss, *Multiagent systems: a modern approach to distributed artificial intelligence*: The MIT Press, 2000.

[8] L. Monostori*, et al.*, "Agent-based systems for manufacturing," *CIRP Annals – Manufacturing Technology,* vol. 55, pp. 697-720, 2006.

[9] S.J. Russell*, et al.*, *Artificial intelligence: a modern approach*. Upper Saddle River (USA): Prentice Hall, 2010.

[10] H.V.D. Parunak, "Applications of distributed artificial intelligence in industry," *Foundations of distributed artificial intelligence,* vol. 4, pp. 139-164, 1996.

[11] Y. Demazeau, "From interactions to collective behaviour in agent-based systems," in *Proceedings of the 1st European Conference on Cognitive Science*, Saint-Malo (France), 1995.

[12] L.E. Parker, "Current state of the art in distributed autonomous mobile robotics," *Distributed Autonomous Robotic Systems,* vol. 4, pp. 3-12, 2000.

[13] G. Baldassarre*, et al.*, "Evolving mobile robots able to display collective behaviors," *Artificial Life,* vol. 9, pp. 255-267, 2003.

[14] M. Pechoucek and V. Marík, "Industrial deployment of multi-agent technologies: review and selected case studies," *Autonomous Agents and Multi-Agent Systems,* vol. 17, pp. 397-431, 2008.

[15] S. Bussmann, "An agent-oriented architecture for holonic manufacturing control," in *Proceedings of the First Open Workshop IMS Europe*, Lausanne (Switzerland), 1998, pp. 1-12.

[16] M. Schillo and K. Fischer, "Holonic multiagent systems," *Manufacturing Systems,* vol. 8, pp. 538-550, 2002.

[17] K. Fischer*, et al.*, "Holonic multiagent systems: A foundation for the organisation of multiagent systems," *Holonic and Multi-Agent Systems for Manufacturing,* pp. 1083-1084, 2004.

[18] M.P. Gleizes and A. Karageorgos, "Self-Organisation and Emergence in MAS: An Overview," *Informatica,* vol. 30, pp. 45-54, 2006.

[19] J.H. Christensen, "Holonic manufacturing systems: initial architecture and standards directions'," in *Proceedings of the 1st European Workshop on Holonic Manufacturing Systems*, Hannover (Germany), 1994.

[20] B. Raveh*, et al.*, "A Little More, a Lot Better: Improving Path Quality by a Path-Merging Algorithm," *IEEE Transactions on Robotics,* vol. 27, pp. 365-371, 2011.

[21] L. Biagiotti and C. Melchiorri, *Trajectory planning for automatic machines and robots*: Springer Verlag, 2008.

[22] E. Sahin, "Swarm robotics: From sources of inspiration to domains of application," *Swarm Robotics,* pp. 10-20, 2005.

[23] C. Blum and D. Merkle, *Swarm intelligence: introduction and applications*. New York (USA): Springer Verlag, 2008.

[24] E. Sahin*, et al.*, *Swarm robotics*: Springer, 2005.

[25] T. Fong*, et al.*, "A survey of socially interactive robots," *Robotics and autonomous systems,* vol. 42, pp. 143-166, 2003.

[26] S. Camazine, *Self-organization in biological systems*: Princeton University Press, 2001.

[27] M. Dorigoa*, et al.*, "Ant algorithms and stigmergy," *Future Generation Computer Systems,* vol. 16, pp. 851-871, 2000.

[28] M. Habib, "Mechatronics - A unifying interdisciplinary and intelligent engineering science paradigm," *IEEE Industrial Electronics Magazine,* vol. 1, pp. 12-24, 2007.

[29] Q. Tang and P. Eberhard, "A PSO-based algorithm designed for a swarm of mobile robots," *Structural and Multidisciplinary Optimization,* pp. 1-16, 2009.

[30] R. Bogue, "Swarm intelligence and robotics," *Industrial Robot: An International Journal,* vol. 35, pp. 488-495, 2008.

[31] F. Mondada*, et al.*, "Swarm-bot: From concept to implementation," in *Proceedings of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS '2003).* 2003, pp. 1626-1631.

[32] M. Dorigo*, et al.*, "The swarm-bots project," *Swarm Robotics,* pp. 31-44, 2005.

[33] A. Decugniere*, et al.*, "Transport of Multiple Objects in the Swarmanoid Project," Institut de Recherches Interdisciplinaires et de Développements en Intelligence Artificielle (IRIDIA), 2008.

[34] *Swarmanoid hardware*. Available on-line at URL: http://www.swarmanoid.org/swarmanoid_hardware.php.