Human Adaptive Mechatronics

Skill Acquisition in Machine Manipulation

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This article explains the background of human adaptive mechatronics (HAM) and the skill level of individuals to operate machines. It is natural to consider both human and environmental factors in the field of robotics and mechatronics. The progress of machines cannot be achieved without paying attention to these factors; a culture that accepts that this evolved through the contributions of many researchers and developers. Prof. Fumio Harashima contributed to the development of HAM significantly. He has done cooperative research with many companies (Hitachi, Toshiba, Mitsubishi Electric, Fuji Electric, Toyo Electric, Dengensha Co., Toyota Corp., Tohoku Electric Power Co., Sumitomo Heavy Machine Corp., Yazaki Corp., and many others) and promoted several large research projects concerned with this culture, such as “Electromagnetic Interference” in the Japan Society for the Promotion of Science project (1998–2003), “Interaction and Intelligence” in the Sakigake Project (2001–2006) [1], and “Human Adaptive Mechatronics” in the HAM project by coordinating with Prof. Furuta during 2004–2008 [2]. The HAM project was initiated by Prof. Harashima and Prof. Furuta, my supervisors when I was a student at the Tokyo Institute of Technology, and this project gave me an opportunity to meet Prof. Harashima.

What Is HAM?

Machines were created to make human life convenient and comfortable. However, humans need training to adapt with the machines effectively. A machine often requires long training and can inflict mental pain and fatigue in humans. Is this circumstance a contradiction? This simple question led to the idea of HAM. Prof. Furuta states “HAM involves intelligent mechanical systems adapting themselves to the skills of humans in various environments and also assisting in improving human skills, such that the human–machine
system achieves optimum performance” [3], [4]. Let me explain the concept of HAM by using an example of an electrical arm (Figure 1). An electrical arm is a type of mechatronics system, including actuated artificial arm or fingers that are driven by the wearer’s myoelectric signal. Basically, the wearer (a human) has to repeat training to adapt to an electrical arm (a machine). To overcome this problem, many studies try to improve motion control and reduce the wearer’s burden. If the wearer’s skill level can be estimated and the dynamics and motions of the artificial arm can be adaptively changed, it can be expected that the wearer enhances one’s skill favorably. Such adaptability to an individual skill level is the first property of HAM. Moreover, if an assistance control of a powerful action is possible, the wearer’s ability is enhanced from the original level; this is the second property of HAM.

The concept of HAM was born through the amalgamation of Prof. Harashima’s opinion that human factors must be considered in future mechatronics and supermechanosystems, which is an advanced design scheme concerning mechanical systems and control theories driven by other Centers of Excellence (COE) projects promoted by Prof. Furuta and Prof. Hirose (1997–2001) [4]. Apparently, the starting point of the HAM project was the New Year’s ceremonial party at Tokyo Denki University in January 2003, where Prof. Furuta and Prof. Harashima first conversed with each other. Project members were then organized, the research plan discussed, and a proposal for the 21st century COE program grant was prepared. The COE program was established in 2002 to cultivate a competitive academic environment among Japanese universities by giving targeted support to the creation of world-standard research and education bases under the Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT). Luckily for me, I got involved in the planning phase of making the proposal to MEXT. Fortunately, for all members of the HAM-COE, the proposal was accepted. I moved to a research group whose subleader was Prof. Harashima. Given that history, I wrote this article because I thought that it was my duty to introduce HAM-COE. To study HAM, disciplines beside mechanical and electrical engineering, such as control systems, information technology, computers, human engineering, psychology, and medical science, are required. Therefore, various specialists cooperated in the HAM-COE project. This article will discuss several types of studies that Prof. Harashima and other colleagues have pursued.

**What Is a Skill?**

The main concern in the HAM research is skill (or proficiency). A definition of skill for a limited application, e.g., piloting an aircraft [5], can be found; however, a general and comprehensive scheme that treats the skill in machine manipulation was not found. This is because the concept of skill itself is ambiguous. In some instances, the term “skill” indicates a primitive action, such as skill-based behavior in Rasmussen’s model [6]; in other instances, this term expresses knowledge-based optimization such as task planning and scheduling; thus, the interpretations of skill are quite broad. I feel that

**FIGURE 1 – Conceptual example of HAM: an electrical arm.**

NIRS is a noninvasive measurement system that can measure the brain activity of natural behavior in a nonrestrictive environment.
coherent definitions and models of skill were significant for establishing a general system design method, which was one of the goals of the HAM project. Since the hierarchy of human behavior shown by Rasmussen’s model (Figure 2) is acceptable to many researchers, I think that the following hierarchy of skills is useful for the HAM study.

L1) **Skill in Cooperation**: Conversation, negotiation, and division of roles

L2) **Scheduling Skill**: Planning of tasks and optimization of work processes

L3) **Cognitive Skill**: Recognition of circumstances and understanding of meanings

L4) **Task Skill**: Execution of segmented subtasks or actions

L5) **Skill for Voluntary Motion**: Manipulation of interface devices and control of machine motion

L6) **Skill in Perception**: Sensing and observation.

This hierarchy was obtained by ranking several types of skills that were required for a work using machines. The L1 is the highest level, and L6 is the lowest one. The primitive levels correspond to perception and motor control in our body nerve system (L6–L5). Such muscle control is called voluntary motion, and the voluntary motion is significant for the machine input device operation that affects the machine’s movement. As a result of machine action, the circumstance around the machine and the status of task change dynamically. Hence, the operator has to recognize such changes (L4–L3). Further, planning of tasks is required since the purpose of the machine manipulation is an achievement of the objective of some job, because operational procedure has to be arranged depending on planning (L2). Social interaction with other team members is also important, since most of the work is performed by cooperation (L1).

Adequate processing on each level and coordination among different levels are required for skilled operation. Although correlation between contiguous levels is high, this is not a rule; for instance, cognitive skills (L3) strongly relate to perception skills (L6) and also have a relationship with other levels. To promote the complex HAM study efficiently, quantification of the skill level based on the hierarchy and assistance corresponding to the quantified skill are necessary.

Along with being an engineering field, the HAM concept requires the understanding of humans. Therefore, all types of skill levels and assisting methods could not be adequately investigated during the research period for the past five years. Some research activities will be explained later, with comments concerning other related topics.

### Assistance for Voluntary Motion

When a human tries to move his/her body parts, the brain controls the musculoskeletal system through musculoskeletal internal models that have already been learned in the cerebellum [7]. Thanks to this excellent mechanism, a human can freely move his/her hands and legs without a thought. These are called voluntary motions regardless of the amount of consciousness required. Concerning the voluntary hand motions and reaching actions, several models such as minimum jerk motion model [8] and minimum variance model [9] have been developed. The voluntary motion is significant whenever a human manipulates a machine. Human voluntary motion directly affects machine movement, because the human and machine form a closed-loop system via a hardware interface (a handle or a joystick). Since the dynamics of a machine is unknown to a beginner driver (or operator), an internal model of the dynamics has to be formed in the brain using a feedback-error learning mechanism [10]. This process is the basic principle of acquiring a skilled operation, and the hand-voluntary motion is adequate for studying the skill; hence, our research group studied hand positioning and its assisting methods through a positioning task with a haptic interface device (Figure 3). In our study, a method for identifying operator control characteristics and evaluating the skill level was...
presented, and an assistant control with a tiny force addition was proposed. As a result, experimental analysis of participant data demonstrated that the assistant control could enhance operator learning [11]. As the haptic sense can transmit assisting information from the machine to a user easily and quickly, a physical interaction between the user and machine is desirable. The benefit of the haptic sense is that it is easy to understand when compared with other types of information; visual information or voice-guidance systems demand cognitive processing that produces a larger time delay than somatic sensations [12]. Of course, a combination of haptic sense and other types of information is effective for better operation. Actually, an operator using a haptic device normally utilizes visual information of controlled objects and infers the machine status from the sound of the machine. At the stage of the system design or problem solving, a segmentation strategy based on the aforementioned skill hierarchy model appears effective, since controversial points of an assist approach will become clear.

Is a Skilled Operator a Good Observer?

One well-known story is that a Japanese neuroscience researcher who wanted to elucidate the nerve system started his study through the development of an aquafarming of squid, because the nerve fiber is suitable for anatomical analysis. Similarly, the most significant factor is human, although HAM is a study of mechatronics. Therefore, the project leaders told me that we should investigate a human before studying the assisting of system design. For this reason, a brain-monitoring system using near-infrared spectroscopy (NIRS) was introduced in our university. NIRS is a noninvasive measurement system that can measure the brain activity of natural behavior in a nonrestrictive environment. Participants can move their bodies more freely when compared with other noninvasive methods; hence, NIRS is adequate to monitor the brain of a user who is operating a machine.

Here, let me explain the relationship between voluntary motion required for machine operation and brain function. Voluntary motion control relates to three areas in the brain: the sensory sphere for perception, the motor area controlling commands for the muscles, and the premotor cortex (PMC) for motion planning. Motions of the hands and legs are normally controlled by the cerebellum; however, the cerebral cortex plays a significant role in acquiring new motion control functions. Functions of the brain are differentiated roughly into local areas, as shown in Figure 4(a) [13]. The primary motor (MsI) and the primary somatosensory (Sml) cortices are important for voluntary motion, and the movements of most muscles in the body are controlled by local regions in these cortices. The correspondence relationship is known as the motor and sensor homunculus. The fold that separates the parietal lobe from the frontal lobe is called the central sulcus. Figure 4(b) shows a cross-section of the brain at the central sulcus. NIRS can monitor these areas because they are in the cerebral cortex.

Our study investigated a topographical map of the brain activity of a user manipulating the machine device. Balancing a virtual inverted pendulum was adopted as a training task. Studies of balancing a stick or an inverted pendulum are widely employed for understanding human neural control: for instance, an analysis of human on-off intermittency strategy on stick balancing [14] and a property analysis of human manual control [15]. In our previous studies, an average of seven days of training was performed for more than 15 participants, and the data were measured. Figure 5(a) shows the experimental setup. The participants sat in a chair and, using their non-dominant hand, manipulated a grip equipped with a slider on the interface device. For the analysis of voluntary motion, a large area covering the supplementary motor area (SMA), PMC, MsI, and Sml was monitored, as shown in Figure 5(b).

The topographical images were computed using principal component analysis (PCA). Figure 4(c) shows an example of the PCA analysis indicating brain activation. The color image shows the strength of decomposed distribution of the topographic pattern. The red areas show strongly activated areas, and the blue areas show weakly activated areas. In our study, the brain analysis of the high-performance participants led to three suppositions about skill acquisition in the balancing task [16]: 1) there was a utilization of sensory information over a wide body area, 2) there was reinforcement of the active visual sensing by cooperation between the ocular motor control in MsI and visual processing in PMC, and 3) there was a relative decrease in the motor control activation of the hand when compared with other areas (although hand motion is required to manipulate the slider).

From these suppositions, it can be deduced that an expert attempted to become a sensitive observer. This suggests that a visual interface enhancing the user’s attention to the movement of the controlled object is preferable.

Gaze and Skill in Manipulation

Locomotive machines such as cars, airplanes, and ships are representative of human-in-the-loop systems and are quite useful for enlarging human activity. However, driving is usually difficult for beginners, because internal models for moving our bodies are not directly helpful for manipulating the vehicle. This is due to the different dynamics of the machines. On the other hand, as shown in the previous section, a person skilled at dynamic manipulation becomes a good observer. This indicates that the skill level of individuals can be evaluated from the user’s gaze behavior. The existence of differences in gazing patterns between an expert and a beginner in Japanese chess or video games has been reported [17]. An analysis of gazing
behavior is effective in understanding cognitive processing. However, the correlation between the gaze and user-control characteristics was not sufficiently investigated from the viewpoint of control engineering. Therefore, in our study, a correlation analysis was performed using the gaze measurement system and system identification method.

Driving consists of many segmented actions, and a driver unconsciously specifies references (or subgoals) for each action while driving. In short, setting subreference targets and execution of each action are performed simultaneously. Good harmonization is necessary for good driving. This concept resembles the module selection and identification control (MOSAIC) model [18], which is an expansion of the feedback-error learning model. Our research group focused on the switching of references and investigated it experimentally. A hovercraft simulator was built as it was difficult for a person to operate (Figure 6), and a course based on a giant slalom skiing course was designed. Several flags were put in the...
game course, and the operator drove the hovercraft by passing through all flags. The manipulation and eye-gaze motion were measured. After the gaze coordinate value on the monitor was transformed to its three-dimensional (3-D) gaze position in the virtual 3-D game space, the complete operation sequence was segmented into subcontrol modes by checking the switching of seeing by using the eye-gaze motion data. The elevation angle, distance, and horizontal angle against the flags were computed. The operator control characteristics were identified by the piecewise autoregressive model with exogenous variables (ARX) model using the aforementioned variables and operator input commands. As a result of statistical analysis of the identified parameters from the learning data of participants, the following facts were confirmed: 1) In the beginner phase, participants depended too much on changes in the elevation angle to the object displayed on the monitor screen. 2) The skilled operator appears to have reconstructed the virtual 3-D space inside the brain from two-dimensional (2-D) image information, because he/she increases the control gains concerning the variables of the virtual 3-D positional relationships. From the analysis, it was confirmed that early switching of subcontrollers or reference and enhancement of the space perception were significant for skilled manipulation [19].

**Evaluation of Skill from Hand Motion**

When any system that has a relationship with a human is designed, a mysterious and interesting human factor, cognition, must be taken into consideration. Since the same is true in the case of HAM, it would be able to support a user adequately if the machine could recognize the status of the same circumstance that the user observes. Researchers are actively studying human cognition with various types of robots or interactive machines. The international research project cognitive robots companions (COGNIRON) [20], which is concerned with robot companions for human-centered environments, and the Anthropomorphic Assistance Systems (MORPHA) project [21], which studies interactions with intelligent robot assistants, are attractive and quite interesting. As a modeling tool for explaining human cognitive processing, goals, operators, methods, and selection rules (GOMS) [22] and Norman's seven stages of action [23] are popular. The model of the seven stages of action comprises perception, interpretation, evaluation, goal, intention, planning, and execution. Studies of the behavior design for robots or the analysis of human actions based on these models are active; however, these models are not utilized sufficiently to design human support systems. The difficulty may come from a large variety of skills required, as shown previously by the hierarchical model of skill level, and a perfect elucidation of the skill as well as its cognition may be difficult. However, unnatural and nonsmooth action that occurs because of certain unskilled factors appears to be detected easily. In other words, the detection of unnatural motions may be effective for evaluating skills. A representative example is a jerky hand-reaching action known as microslip presented by Reed and Schoenherr [24]. In our preliminary study, the relationship between task performance and microslip level was investigated through a coffee-making test, and a high correlation was confirmed [25]. This result indicated that the skill of task scheduling can be estimated by checking tiny changes in hand motions.

Another interesting behavior of a hand-reaching action is known as Fitts’ law. Fitts’ law is an experimental formula of the relationship between the time and distance of voluntary hand motions [26]. This law is valid for a reaching action with feet or other body parts, with hand in the water and nonstraight line courses [27]. Fitts’ law is used for evaluation of computer interface designs such as a graphical user interface (GUI) [28] or a stylus [29]. In general machine operation, reaching actions inevitably occur because machines are typically equipped with multiple switches. Therefore, an evaluation method based on Fitts’ law can be utilized as a skill estimator in the HAM system. In our study, a remote operation system was built that simulated operation of actual construction equipment, as shown in Figure 7, and the process of learning its operation was analyzed. As a result, statistical analysis using the data of ten participants showed a sufficiently high correlation between

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**Studies of balancing a stick or an inverted pendulum are widely employed for understanding human neural control.**

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![Figure 6](image-url)

**FIGURE 6** — (a) An experimental scene of the virtual hovercraft manipulation and (b) information for identifying user characteristics.
An analysis of gazing behavior is effective in understanding cognitive processing.

change of the fitting error to Fitts’ law and the task performance index. That is to say, reaching actions of users fit to Fitts’ law gets better as the skills improve [30]. Since the approach using Fitts’ law can be implemented in a computer and executed automatically, this is more desirable for the realization of HAM than an approach based on microslip, because the latter requires the judgment of human analysts.

**Automatic Classification of Operating Modes**

In the previous subsections, several approaches for evaluating skill with machine operations were mentioned. However, the issue of machine recognition is one of circumstance still remains. To develop machine recognition, it is helpful to refer to a mechanism of human recognition. As a tool for qualitative investigation of human actions, task analyses have been developed and are often utilized in manufacturing management. Several tools for task analyses, for instance, Therblig [31], can be applied to skill analysis; however, the tools are not adequate for automatic computation because the task contents depend on the type of work, and qualitative analysis requires human experience. Such qualitative analysis requires an algorithm that segments the continuous operation of a human into fragments. This comes down to a clustering problem of multivariable time-series data involving operator manipulation and environmental changes. The condition for clustering in this case is, however, not good, because human motion includes discrete and undesirable motions caused by human error. For this reason, an orthodox approach, such as discriminant analysis, nearest neighbor method [32], and fuzzy clustering is inadequate because of its requirement of a large data set. A self-organizing map (SOM) [33] was used in our study. The SOM technique makes cluster regions on a 2D map by conserving the topological information. In our previous study, an analysis procedure that makes the task-switching profile visible was presented, and a new cluster-growing method was proposed [34]. Correlation analysis demonstrated that the distances among decomposed clusters corresponding to segments of the operation strongly relate to a performance index of the task. This approach, which imitates a mechanism of the brain, can segment human sequential actions and can show differences in the skill of the operating-mode switching.

**Epilogue**

This article introduced several research activities that were promoted by Prof. Harashima and other colleagues. As part of the HAM-COE project, 19 promoters, 14 cooperative researchers, five research assistants, and many students cooperated. The following are internationally known experts who supported the HAM project and promoted studies with original members of the HAM research:

- K.J. Åström (Lund University); Z. Bien (KAIST); M. Buss (Technical University of Munich); E.J. Davison (University of Toronto); W.P. Dayawansa (Texas Technical University); M. Egerstedt (Georgia Institute of Technology); B. Gosh (Texas Technical University); K. Kawamura (Vanderbilt University); D.S. Kwon (KAIST); C. Martin (Texas Technical University); D. Owens (University of Sheffield); C. Park (Kyung Hee University); K.B. Sim (Chung-Ang University); T.J. Tarn (Washington University); M. Tomizuka (University of California at Berkeley); J. Vain (Technical University of Estonia); L. Vlacic (Griffith University); and H. Yu (University of Staffordshire).

Because various researchers joined the HAM project and then spread the research field widely, many research themes have been studied. HAM theories for safe manual control [35] and the rate saturation of actuators and intermittency control [36] were actively studied. A surgery support system [37] was developed as a demonstration equipment of the HAM concept. Also, many workshops and special sessions were held at international conferences, such as the 2004 and 2005 International Conference on Mechatronics Technology, 2005 and 2006 International Symposium on Robot and Human Interactive Communication, 2002 and 2005 International Conference on Control, Automation, and Systems, 2006 Conference on Control Applications/CACSD/ISIC Joint Conference and 2008 International Conference on Systems, Man, and Cybernetics.

The COE workshop on HAM was held every year, and the COE activities during the five years were discussed at the final fifth workshop. The discussions concluded that much had been done through HAM-COE, but many challenges remained in aspects of...
HAM’s technical, educational, and commercial development. Concerning the future of HAM, the following comments were given: 1) mutual adaptation between human and mechatronics system was recommended to be promoted and 2) the scope of the HAM should be coherent by more inter and intraactivities of research teams. As a comment, two possible names for future HAM were suggested. Prof. Kawamura suggested iHAM for true integration of three key words: human, adaptive control, and mechatronics. Prof. Buss suggested eHAM for electronics HAM. For the extension of the HAM concept, both professors intended to enhance HAM philosophy. Prof. D.H. Owens, from the University of Sheffield, states “The real situation is, however, more complex with a need to examine issues.” I would like to continue to work to resolve such complexity in my research life.

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Biography
Satoshi Suzuki (ssuzuki@fr.dendai.ac.jp) received his B.S. degree in control engineering, M.S. degree from the Department of Systems Science, and Ph.D. degree from the Department of Mechanical and Control Engineering from Tokyo Institute of Technology in 1993, 1995, and 2004, respectively. From 1995 to 1999, he was a development engineer working for TOSHIBA Corporation at the Heavy Electrical Laboratory. In 1999, he moved to Tokyo Denki University and studied methods of human-behavior analysis with the 21st century COE project office. He is currently an associate professor at the Department of Robotics and Mechatronics. He is a Member of the IEEE, Society of Instrument and Control Engineers, and Japan Society of Mechanical Engineers. His research interests include human–machine system, control theory, and robotics.

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