Overview of Human Adaptive Mechatronics

Hongnian Yu

Faculty of Computing, Engineering and Technology
Staffordshire University, Stafford, ST18 0DG, UK

Abstract: - Human adaptive mechatronics is intelligent electrical-mechanical systems that are able to adapt themselves to the human's skill in various environments, and provide assistance in improving the skill, and overall operation of the combined human machine system to achieve improved performance. It is clear that humans have strong and extremely adaptive natural mechanisms that are able to accommodate external environmental disturbances under which internal life cycle operations can still be regulated very effectively. It has been of great interest to human beings to apply similar biologically-inspired mechanisms to man-made systems such as mechatronically built robots, unmanned air vehicles, airplanes, auto pilot steering systems, engineering ergonomics, and numerous examples encountered in autonomous systems. It aims to study automata from an engineering perspective and to serve the purpose of controlling advanced engineering systems. The improvement in human-machine interfaces has made advanced intelligent machines possible without special education and training. This paper will introduce the basic concepts of human adaptive mechatronics, review aspects of the research in HAM conducted over the last five years, and presents two HAM-related case studies.

Key-Words: - Human Adaptive Mechatronics, Robotics, Mechatronics, Human Science, Intelligent Control

1 Introduction

The concept of human adaptive mechatronics (HAM) was first proposed by the 21st century centre of excellence (COE) at Tokyo Denki University (TDU) in 2003 [1][2]. During the past five years, the members of the COE centre have conducted significant research on HAM and have published 146 journal papers and 388 international conference papers [3]. TDU COE organized 5 COE Workshops on HAM, one international TDU-UK EPSRC Workshop on HAM in July 2005 and one joint international workshop on HAM and High Fidelity Tele-presence in October 2005, and have organized numerous special sessions and issues on HAM. Since then, the UK-Japan HAM network has been set up (in March 2007). Research conducted by the network members can be viewed on the network website (www.EPSRCHAMNetwork.org.uk).

HAM is intelligent electrical-mechanical systems that are able to adapt themselves to the human's skill in various environments, and provide assistance in improving the skill, and overall operation of the combined human machine system to achieve improved performance. The key idea of HAM is to develop a system which includes the human in the control loop and changes the functions and structure of man-machine interface to improve the human's operational skills. It is clear that humans have strong and extremely adaptive natural mechanisms that are able to accommodate external environmental disturbances under which internal life cycle operations can still be regulated very effectively. It has been of great interest to human beings to apply similar biologically-inspired mechanisms to man-made systems such as mechatronically built robots, unmanned air vehicles, airplanes, auto pilot steering systems, engineering ergonomics, and numerous other examples encountered in autonomous systems. HAM aims to study automata from an engineering perspective and to serve the purpose of controlling advanced engineering systems. The improvement in human-machine interfaces has made advanced intelligent machines possible without special education and training. HAM research covers the following fields:

- Fundamental theory of HAM
- Modelling human and machine dynamics under the constraint environments
- Modelling and identification of the psycho-physical characteristics of a human user
- Intelligent control methodologies for HAM
- Identification of human behaviour and operation
- Human intelligence, learning, and understanding including cognition
- Assistive robotics and mechatronics

- Human-machine, computer and mechatronics interface
- Medical applications of HAM
- Sensors and actuators in HAM
- HAM applications

This paper reviews the existing HAM research. The basic concepts and core elements of HAM are presented in Section 2. Two case studies, the pendulum-driven cart pole system and the capsule robot, which are currently being researched by the author's research group, and some other examples of HAM-motivated applications are given in Section 3. Section 4 draws the conclusions and considers future research.

2 Basic concepts of HAM

The area of HAM is a multidisciplinary combination of Intelligence & Control, Mechatronics, Computer Science and the subject of human-machine interaction, as shown in Figure 1. Its applications include the medical arena, engineering diagnosis, disaster rescue, service, etc. Study of HAM requires knowledge of cognitive science, robotics, human-computer interaction, human-machine systems, AI & intelligent machines, and networked monitoring & control systems.

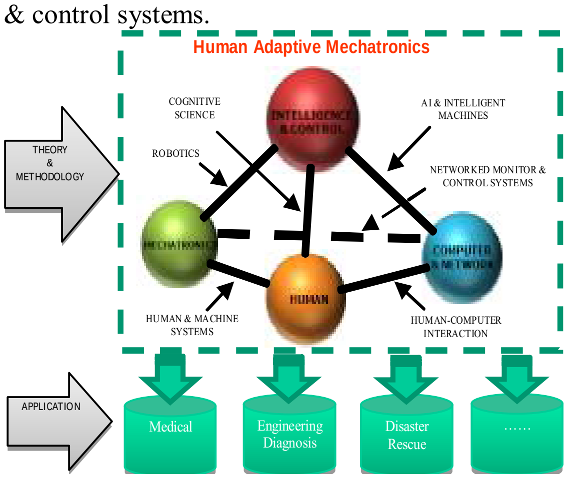

Figure 1 Human Adaptive Mechatronics

2.1 Intelligent control

Intelligent control [6] involves applying various AI techniques, such as neural networks, Bayesian probability, fuzzy logic, machine learning, evolutionary computation and genetic algorithms etc. within the discipline of control systems to produce a robust autonomous system which can adapt itself to environmental change. Intelligent control achieves automation via the emulation of biological intelligence by either seeking to replace a human who performs a control task (e.g., a chemical process operator) or borrowing ideas from biological systems to solve problems and to apply them to the solution of control problems (e.g., the use of neural networks for control). Examples of intelligent control techniques are

- Fuzzy control - a methodology to represent and implement a (smart) human's knowledge about how to control a system
- Artificial neural networks - which use circuits, computer algorithms, or mathematical representations loosely inspired by the massively connected set of neurons that form biological neural networks. Artificial neural networks are an alternative computing technology that have proven useful in a variety of pattern recognition, signal processing, estimation, and control problems.
- A genetic algorithm - a computer program that simulates characteristics of evolution, natural selection (Darwin), and genetics (Mendel)
- Expert control systems – which are used as a feedback controller with reference input (desired output) and feedback variable (output) by using the information in its knowledge base and its inference mechanism to decide what command input to generate for the plant
- Iterative learning control – which differs from most conventional control methods in the sense that it exploits every possibility to incorporate past control information, such as tracking errors and control input signals, into the construction of the present control action. There are two phases: first the long term memory components are used to store past control information; then the stored control information is fused in a certain manner so as to ensure that the system meets control specifications such as convergence, robustness, etc. It is worth pointing out that those control specifications may not be easily satisfied by other control methods as they require more prior knowledge of the process in the stage of the controller design. Iterative learning control requires much less information of the system variations to yield the desired dynamic behaviours.

Intelligent control not only tries to borrow ideas from the sciences of physics and mathematics to help develop control systems, but also biology, neuroscience, artificial intelligence, and other areas. It has proven useful in some applications in many fields, and may offer helpful solutions to the challenging problems that we encounter.

2.2 Mechatronics

Mechatronics, a term coined in Japan in the late 1960's, is the synergistic combination of precision mechanical engineering, electronic engineering, software engineering and systems thinking in the design of products and manufacturing processes. The purpose of this interdisciplinary engineering field is the study of automata from an engineering perspective, and it serves the purposes of controlling advanced hybrid systems. The discipline of mechatronics has been developed through the interdisciplinary studies of diverse engineering fields.

Mechatronics has widely been used in almost all aspects of human life and welfare and has improved the quality of human life. The academic field of mechatronics has been well developed, and many courses on mechatronics [9] have been introduced into university engineering departments. Mechatronics research cover a wide range of application areas including consumer product design, instrumentation, manufacturing methods, computer integration and process and device control, and attracts a readership from across the industrial and academic research spectrum. Particular importance is attached to aspects of innovation in mechatronic design philosophy which illustrate the benefits obtainable by an *a priori* integration of functionality with embedded microprocessor control. There are many journals dedicated to mechatronics research topics [10][11].

From the above, we can see that the aim of mechatronics is to design an electronic-mechanical device which outperforms the conventional mechanical devices without properly considering the human factors. The key difference between mechatronics and HAM is that HAM is trying to develop a device which can adapt to the skill level of users and can improve their operation skills.

2.3 Computer and Networks

Computer science is the study of the theoretical foundations of information and computation and their implementation and application in computer systems, while Computer networking is the engineering discipline concerned with communication between computer systems or devices. Computer networking is sometimes considered a sub-discipline of telecommunications, computer science, information technology and/or computer engineering. Computer networks rely heavily upon the theoretical and practical application of these scientific and engineering disciplines. A computer network is any set of computers or devices connected to each other with the ability to exchange data.

Computers and networking have greatly changed human life; they have been applied in almost all areas of society, and, where used properly, have improved the quality of life and welfare significantly. Students now study ICT in primary school.

2.4 Human Sciences

Human science [13] is the study and interpretation of the experiences, activities, constructs, and artefacts associated with human beings. The study of human sciences attempts to expand and enlighten the human being's knowledge of his or her existence, its interrelationship with other species and systems, and the development of artefacts to perpetuate human expression and thought. It is the study of human phenomena. The study of the human experience is historical and current in nature. It requires the evaluation and interpretation of the historic human experience and the analysis of current human activity to gain an understanding of human phenomena and to project the outlines of human involution. Human science is the objective, informed critique of human existence and how it relates to reality. The ultimate scientific question is: what is reality? The ultimate question in the study of human beings is: what is the reality of being human? To study appropriate human phenomena it is necessary to use multiple systems of inquiry. Empirical, psychological/philosophical, and spiritual methods of inquiry are the research methodologies associated with the human sciences.

Humanity is a key element of HAM and the issue of modeling and understanding the human factors in a control loop is receiving great interest in current research. Research into human science under the HAM concept includes psychology, philosophy, neuroscience, linguistics, anthropology, etc.

2.5 Cross Elements Knowledge Base

The HAM cross elements generated from Figure 1 are standard lone scientific research areas and have received much attention. The basic concepts of the following terms are available from [13].

2.5.1 Robotics

A robot is an intelligent mechatronics device which has some aspects of human capability. The field of robotics has evolved from industrial robots for manufacturing tasks in the late 1960s, to personal and humanlike robots for service and medical purposes in the 2000s, to biological and intelligent robots in the future.

Biological and intelligent robots should have the following features: 1) ability to deal with uncertainty

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within the systems, such as sensor noise, actuator inaccuracy, and component failure; 2) ability to handle a huge uncertainty in the real world, which is dynamically changing over time. It is difficult to catch up with these changes in real time since no sensor is able to work in all situations and circumstances. 3) ability to address issues inspired by biological systems in the design of intelligent robots, since this could provide some guidance in solving the problem; 4) ability to develop a simple human-robot interaction including communication with and navigation around humans.

2.5.2 AI and Intelligent Machine

AI [12] is both the intelligence of machines and the branch of computer science which aims to create it.

AI research uses tools and insights from many fields, including computer science, psychology, philosophy, neuroscience, cognitive science, linguistics, ontology, operations research, economics, control theory, probability, optimization and logic. AI research also overlaps with tasks such as robotics, control systems, scheduling, data mining, logistics, speech recognition, facial recognition and many others. Other names for the field have been proposed, such as computational intelligence, synthetic intelligence, intelligent systems, or computational rationality.

2.5.3 Cognitive Sciences

Cognitive science is most simply defined as the scientific study either of mind or of intelligence. It is an interdisciplinary study drawing from relevant fields including psychology, philosophy, neuroscience, linguistics, anthropology, computer science, and biology. Cognitive science has a close relationship with AI [12]. Understanding and application of cognitive science in HAM will be an important research issue.

2.5.4 Networked Monitoring and Control Systems

In a report on “Future Direction in Control” [7] prepared by experts in the control community, the control of large complex systems, e.g. the internet, is expected to be one of the main research trends in coming years. The internet represents one of the largest complex man-made networks. It is widely recognised that research in Networks and Control is extremely important. Broadly speaking, this covers two research areas. The first is control of computer/communication networks called control of communication networks (CCN), i.e., to study how the application of control methods to improve quality of service (QoS), for example, internet congestion control, routing control, caching and updating data at multiple locations, managing power levels for wireless networks, etc. CCN has received great attention during the past few years.

The other is networked control systems (NCS) which represents a control system communicating with sensors and actuators over a communication network, i.e., to study how communication networks (wired or wireless) influence control systems. A historical review of the evolution of controller structure for large complex systems and the current research in NCS, such as networked delays, sampling time, jitter, data packet dropout, network scheduling and stability, are presented in [8].

2.5.5 Human Machine Systems

A human machine system is a system in which the functions of the operator and the machine are interrelated and necessary for the operation of the system, also known as man-machine system.

2.5.6 Human-Computer Interfaces

Human–computer interaction is a branch of computer science but with a focus on interaction between users and computers. It is often regarded as the intersection of computer science, behavioral sciences, design and several other fields of study. Interaction between users and computers occurs at the user interface (or simply *interface*), which includes both software and hardware, for example, general-purpose computer peripherals and large-scale mechanical systems, such as aircraft and power plants.

3 Applications of HAM

In this section, two HAM-related case-studies are summarized. The details can be found from [3][4][5].

3.1 Pendulum-driving Cart-pole Systems

The classical pendulum cart system is a benchmark underactuated system that has been widely used in nonlinear control education and research to demonstrate the effectiveness of control systems in analogy with the control of many real systems. Many control issues have been investigated, such as swinging up, stabilizing the pendulum in the upward equilibrium position, and further moving the cart to a desired position. Furthermore, many control strategies based on feedback linearization, energy shaping, passivity, and Lyapunov theory have been extensively studied. Furuta demonstrated the research evolution from super mechano-system to

HAM from the view of modeling and control of an inverse-pendulum [1].

Yu, etc[4] investigated a new special model which is a reversed classical pendulum cart system experiment: the pendulum-driven cart-pole system. Torque is added on the pendulum pivot, instead of the force on the cart. The difference between the classical pendulum cart system and the pendulum-driven cart-pole system is that the former is a stabilization problem and the later is a tracking problem. The purpose of this research is to make the cart track a desired (designed) trajectory by applying a control input torque.

The difference between the classical cart-driven system and the pendulum-driven system is that the former addresses a stabilization problem and the latter addresses a tracking problem. The aim of the cart-driven inverted pendulum shown in Figure 2 is to rotate the pendulum to an upward position and stabilize it by applying a control input force to the cart, while the aim of the pendulum-driven inverted pendulum is to make the cart trajectory track a desired (designed) trajectory by applying a control input torque to the pendulum with the passive cart wheel (with no input force applied to the cart). The dynamic model and control issue of a pendulum-driven inverted pendulum are similar to those of a capsule robot which we are currently investigating.

3.2 Capsule Robots

The capsule-type robot has many potential applications such as medical inspection robots which the patient can swallow. The micro capsule-type robot with sensors will move around in the human body and send the useful medical data to the doctors to help them make correct decisions.

Liu etc [5] has studied the tracking issue of the capsubot has from the viewpoint of the underactuated dynamic system. An optimal seven-step motion strategy has been proposed. A trajectory profile based on the proposed strategy has been generated. Three control approaches have been investigated: the open-loop control law, the closed-loop control law using partial feedback linearization, and the simple switch control law. The simulation results have been presented to demonstrate the proposed approaches. A brief comparison of the proposed approaches has also been made.

The implementation of a lab-based rig is under development. This device consists of three parts: a capsule shell, a piezoelectric element, and an inner mass. An optical encoder is used on the device to measure the position of the capsubot at real time. This system can be used by researchers as a test bed to demonstrate the proposed approach. Further work in this research area will include robust control with parameter uncertainty, iterative learning control using repetitive continuous cycles, and test of the device in a real complicated environment.

3.3 Other Applications

- Human operation with XY-stages
- Haptic systems
- Brain monitoring analysis
- Assisted training system for improving constructional abilities

4 Conclusions and Future Works

This paper has presented the basic structure and concepts of human adaptive mechatronics. Two HAM- related case studies have been presented in detail. The related HAM applications have also been summarized.

In summary, this paper revealed that although much work has been done over the past five years, many challenges remain in aspects of HAM's technical, educational and commercial development. The interest shown world-wide in HAM has been exceptional and research in HAM will and should continue. What about the future? Future research in HAM [3] can be viewed in three aspects: 1) intelligent control, 2) mechatronics and 3) human sciences.

4.1 Intelligent Control

HAM will need to build on the wide range of mathematical and software tools made available by the past 20 years of international research. It can be considered that the main issues are conceptual development and closer integration of control, mechatronics and human behaviour via integration of data and algorithms with hardware and software implementations in a definable, widely- adopted product. The real situation is, however, more complex, and there is a need to examine other issues including:

- Greater integration and involvement of other disciplines in the endeavour. For example, the involvement of researchers from psychology (more precisely, researchers with interests in the psychology of humans interacting with machines) is essential for proper modelling and understanding of the "human in the loop systems" within HAM.
- More fundamental assessments and developments of the tools required for modelling, analysis and control e.g. the development of appropriate tools for nonlinear analysis of

systems based on ordinary differential, discrete, partial differential and hybrid models of HAM systems incorporating aspects of
  - Adaptation
  - Cognition
  - Learning (including learning from failure)
- A greater understanding of the differences between and benefits of human-aided machine operation and machine-aided human performance and the implications of these concepts for HAM systems and algorithm design.
- The development of improved hardware support systems including sensors and actuators to cope with the wide-ranging needs of human-machine systems.
- The creation of a widely recognised design framework for HAM systems.
- A focus on the educational needs of staff and students to ensure the sustainability of a healthy and productive future for HAM in Japan and world-wide. This discussion should cover both undergraduate and postgraduate courses and will need to address the challenge of ensuring an effective multi-disciplinary education from a single subject background. This will include traditional approaches but will also require the integration of theory and application through extensive individual and team-based project work.
- Creating wider awareness of HAM capabilities both through the development of a system that has a global impact academically, and through a commercial product, preferably in an area that improves quality of life e.g. easily used assistive technologies supporting complex tasks or the requirements of an aging population.

In this way, HAM will establish itself as a new mainstream discipline and a preferred discipline of study for many engineering, computing and technology students.

4.2 Mechatronics

- Develop a guideline for the roles of the human and the machine in various HAM systems
- Develop the performance evaluation criteria for HAM-based man-machine systems
- iHAM – integration of the human, adaptive control and mechatronics

4.3 Human Sciences

- How to measure human behaviour including intention and awareness in terms of brain function signals such as low field MRI, single trial, BCI, etc
- Mutual adaptation by the human and the mechatronic system

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