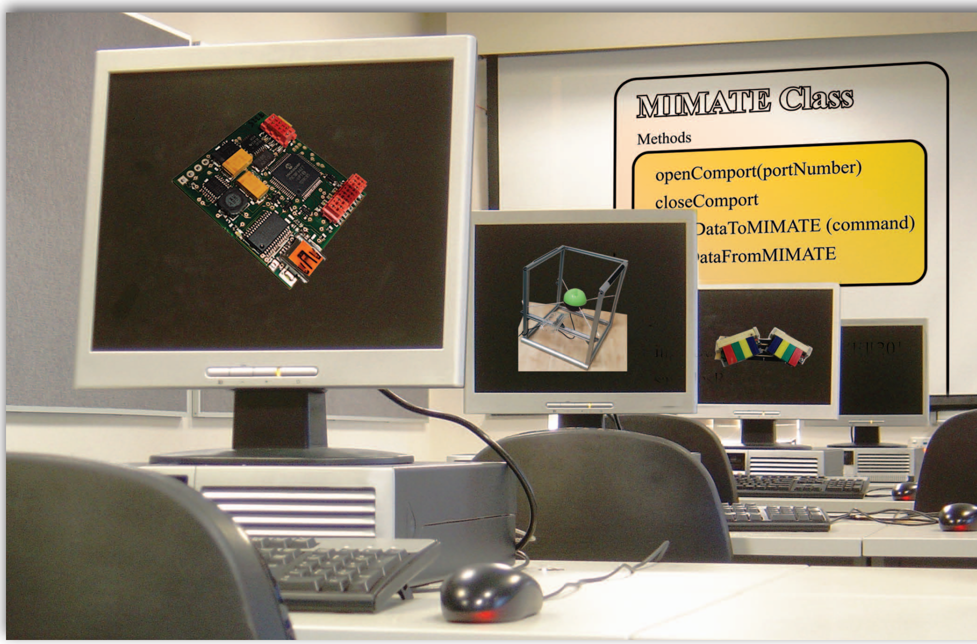
# Learning to Design Rehabilitation Devices Through the H-CARD Course




COMPUTERS COURTESY OF STOCK.XCHNG/GARY TAMIN.

By Nick Roach, Asif Hussain, and Etienne Burdet

## Project-Based Learning of Rehabilitation Technology Design

The aging population and the wish to improve quality of life, as well as the economic pressure to work longer, call for intuitive and efficient assistive and rehabilitation technologies. Therefore, we have developed a project-based education paradigm in the design of assistive and rehabilitation devices. Using a miniature wireless sensing and feedback platform, the multimodal interactive motor assessment and training environment (MIMATE), students from different engineering backgrounds were able to develop innovative devices implementing rehabilitative games in the short span of a one-term course. We describe here this novel H-CARD course on the human-centered design of assistive and rehabilitative devices.

*Digital Object Identifier 10.1109/MPUL.2012.2216719*
*Date of publication: 11 December 2012*

The number and the proportion of individuals affected by neurological diseases [e.g., stroke, Parkinson's disease, cerebral palsy (CP), spinal cord injury, and epilepsy] are increasing worldwide in part due to an aging population. In parallel, the field of rehabilitative and assistive technology has expanded significantly in recent years, and a variety of mechatronic devices have been developed to address the physically debilitating effects of neurological diseases such as stroke and CP [1]. Mechatronic systems have also been developed to detect seizures in epilepsy patients, help blind people find their way, and assist individuals affected by Parkinson's disease.

Rehabilitation technology illustrates the paradigm for emergent systems to assist humans. The success of rehabilitative and assistive systems depends on an intuitive interface, an attractive design, and gamelike applications. Their development depends on the successful integration of a range of disciplines including mechatronics, medicine, psychology, and computer science. Due to the diverse range of skills these disciplines entail, training students in the development of rehabilitation and assistive devices represents a challenge. Integrating psychology or medical students (with little technological knowledge) and engineering students (with little knowledge of human aspects) and having them communicate effectively and learn together is a main issue.

While learning by doing appears to be an efficient teaching method even for classical topics such as physics [2], the design of assistive and rehabilitative devices particularly demands project-based learning [3]. In the 1990s, tools were developed to teach robotics [4] that later gave rise to the Lego Mindstorms kit. More recently, an educational set was developed to teach haptics [5]. However, we were unable to find any system to develop efficient rehabilitative or assistive devices with intense sensory-motor interfaces over the short span of a typical one-term course.

In response to this demand, we created a device for the tutoring of such techniques within the context of an undergraduate teaching environment. The MIMATE module provides a wireless embedded platform for the investigation of sensing and actuation technologies and their integration into human-centered feedback systems. MIMATE was intended to allow students to explore the use of embedded sensing, processing, and control techniques in real applications. It was designed to be usable by students (with little or no expertise in embedded systems and software development) for the development of simple interactive applications using user-friendly graphical user interface-based game-development environments, yet MIMATE is versatile enough for more experienced engineers and programmers to customize and integrate it into complete, clinically useful rehabilitation systems using industry standard interfaces and development tools.

Practically, MIMATE consists of a printed circuit board (PCB) integrating a variety of sensors (gyroscope, accelerometer, and magnetometer) and feedback devices (colored light-emitting diodes (LEDs), a speaker, and vibratory motor) with a low-power microcontroller (Figure 1). A multipurpose interface port provides access to a variety of electrical inputs and outputs, allowing for the connection of additional sensors and actuators. In addition, Bluetooth and universal serial bus (USB) communication links are provided for communication with a host device (e.g., PC, smartphone). The module is lightweight, battery powered, and features a form factor appropriate for integration into wearable or readily manipulated objects. The device is relatively low cost to facilitate easy replacement, and robust to resist damage by mistreatment. Control of the module is achieved by a software library that is common to a variety of development environments. This library provides a simplified minimal set of functions that can be called for collecting sensor reading and generating feedback dependent on the user's application.

The MIMATE module is the key enabling technology in the human-centered design of assistive and rehabilitative devices (H-CARD) undergraduate course that we have pioneered and run for the past two years at Imperial College London, United Kingdom. The course gives an introduction to the design and implementation of assistive and rehabilitative devices, using basic knowledge of pathologies commonly responsible for physical disability. It encourages the development of a range of skills, including human-centered and patient-specific design, mechatronics, project management, and research. Aspects of game and media design are also considered, as these can provide important motivational factors for users of these devices.

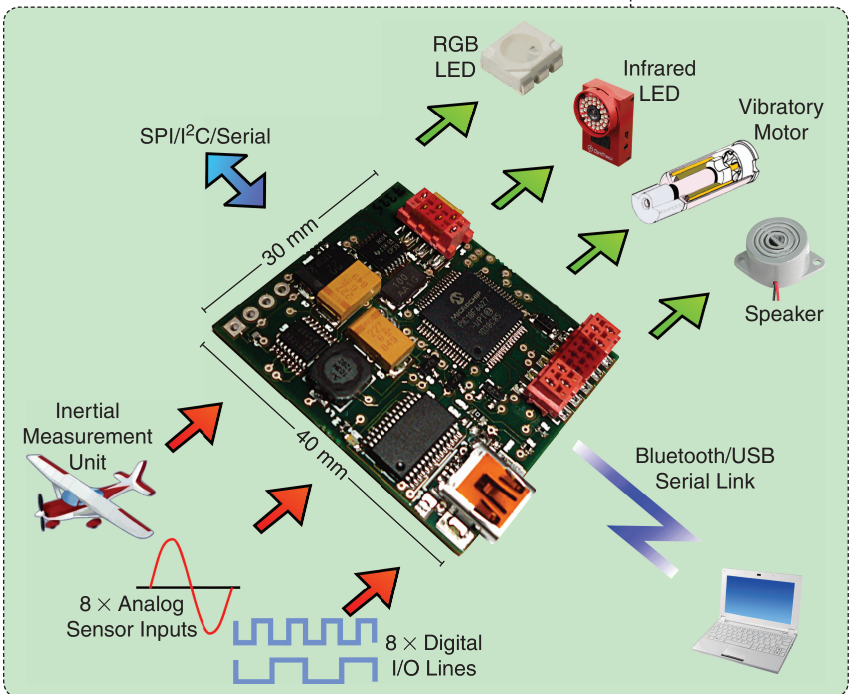



FIGURE 1 A basic MIMATE module and its interfaces. The sensing and stimulus hardware that can be connected to this compact module yields a versatile platform for the development of rehabilitative and assistive devices.

## MIMATE Module

The primary requirement for the design of the MIMATE module was to provide an integrated development platform with which limb movements and physical interaction with objects and the environment can be monitored and appropriate feedback generated. Typical examples of such applications are the training and assessment of reaching and grasping, gait, and basic activities of daily living. Therefore, it was essential that the form factor of the device is appropriate for manipulation by or attachment to the human body. As the device is to be used in education, robustness, low cost, and compatibility with a range of software-development environments are paramount.

### *Specification of Sensing and Feedback Capabilities*

With regard to sensing and feedback capabilities of the module, detection of motion, orientation, and interaction force were considered particularly important for the targeted applications. Feedback from the module was required to provide cues to a user for the purposes of encouragement, physical assistance, or guidance, depending on the application. Visual, vibrotactile, and auditory sensory modalities were selected as the main sensory and feedback modalities, as their effects are known from prior applications and due to the intrinsic safety of derived rehabilitative solutions.

Where possible, both sensors and actuators were integrated directly with the module, allowing for immediate use in the development of simple interactive devices and interfaces, while avoiding external hardware or wiring. The requirement to be self-contained also drove the decision for motion and orientation sensing to be performed on the device, instead of being provided by an external measurement system (such as a machine vision system). Therefore, the module included an inertial sensing element capable of estimating tilt, orientation, vibration, and translation (with limited accuracy) of the device when utilized in conjunction with appropriate signal processing algorithms.

Any wiring on or around a human user presents an inconvenience, if not a hazard for entanglement or electrocution. Therefore, battery-powered wireless operation was considered essential. Additionally, to prevent encumbrance of the user, the module was required to be compact and lightweight, with an appropriate arrangement of components for ease of manipulation. It was also desirable that the device be robust enough to withstand adjustments and modifications by novice students.

### *Hardware Specification of MIMATE*

The physical design of MIMATE was based on a PIC18F6722 8-b microcontroller running at 40 MHz interfaced with a nine-axis inertial sensor composed of a trio of an Analog Devices ADXL345, an InvenSense ITG-3200, and a Honeywell HMC5843, which provide measurements of acceleration, rate of turn, and magnetic field, respectively. These sensors provide measurement ranges of ±16 g, 2,000°/s, and 4 G, with resolutions of 16, 13, and 12 b, respectively. These values were chosen as they encompass the range of these parameters experimentally established for normal human movements. The typical inertial data recorded by MIMATE's sensors during three cycles of a point-to-point reaching movement can be seen in Figure 2. During these movements, MIMATE was attached to the wrist of the participant and temporally synchronized with an external optical tracking system for reference.

For the on-board visual, auditory, and tactile modalities, feedback was provided by a high-intensity multicolor LED with pulse width modulation dimming (Osram SFT722N-S), a magnetic microbuzzer (CUI Inc. CSS-0578), and vibratory motor (Model 310-101, Precision Microdrives), respectively. Three high-intensity wide-angle IR LEDs (Osram SFH421) were also provided to enable simple photogrammetry. Force sensors were not directly integrated into the module due to their application dependence in terms of geometry, range, and accuracy. However, eight general-purpose analog inputs were provided (10-b resolution) via a connector along with appropriate biasing voltages for force-sensing resistors (FSRs).

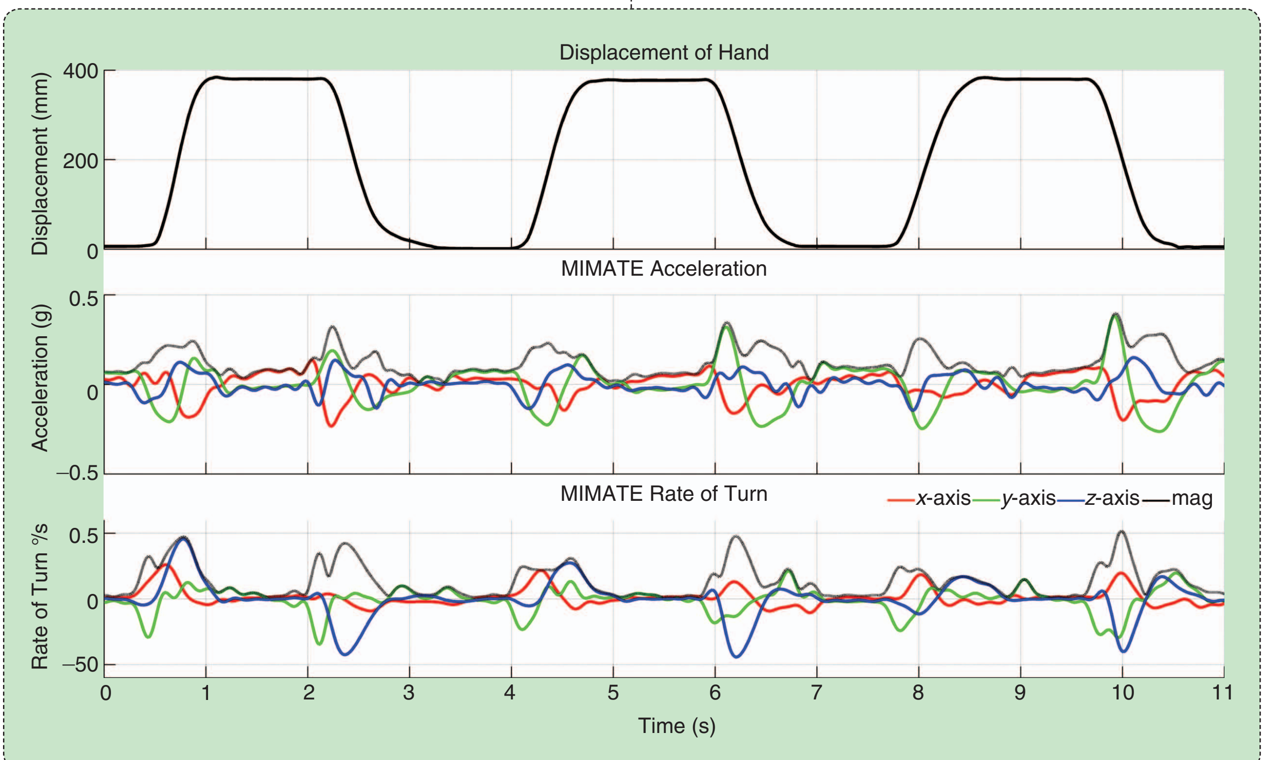



**FIGURE 2** The inertial measurements for a typical reaching task: measured xyz components and magnitude (mag) of acceleration and rate of turn for a repetitive hand movement with MIMATE. Acceleration data was high-pass filtered at 1 Hz to remove offset due to gravity. All signals were low-pass filtered at 15 Hz to remove shock and vibration. The externally measured displacement of the hand is shown for reference.

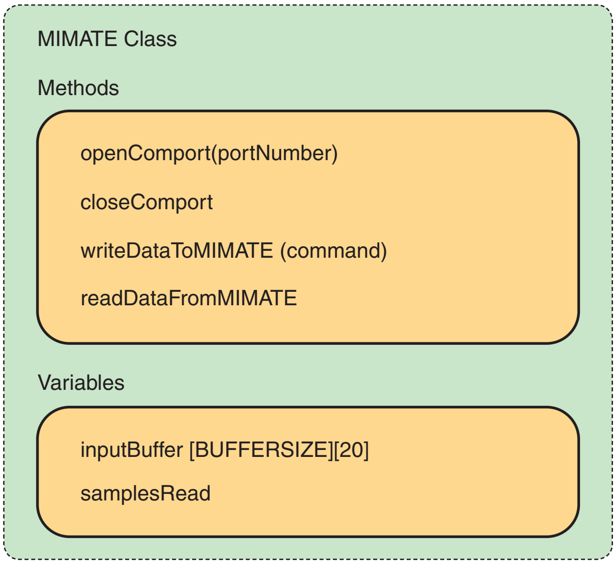



**FIGURE 3** Members of MIMATE class. Minimal public methods and variables allowing access to the MIMATE under C++. The open and close functions allow connection and disconnection from the module, while the write data function allows for control of actuators. The read data function collects and parses data from attached sensors to be accessed in the two variables.

To facilitate integration with other microcontroller devices and more sophisticated sensors/actuators, eight general-purpose input/output (GPIO) lines and a serial port are broken out to connectors along with a single I2C/serial peripheral interface (SPI) bus. The wireless communication capability of the module was provided via an integrated Bluetooth module (KC Communications KC-22) chosen for its small scale and low power consumption (25 mA). This device facilitates a simple serial port Bluetooth link to a host system with a data rate of 230.4 kBaud. Although more power-efficient radio systems are available, Bluetooth was the preferred physical transport due to its relative ubiquity in mobile computing applications.

Power to the module is provided via USB or an integrated battery management IC (MAX1555) and 330 mAh Li-Polymer cell. Regulation of on-board voltages is achieved by a dc–dc converter (MAX1705) providing +3.3 V and +5 V at 1 A. The peak current consumption of the module is ~100 mA. Therefore, ~900 mA is available for user-designated functions. A positive temperature coefficient self-resetting fuse is included in the power input to prevent damage to the power supply circuitry due to accidental overload. The device is assembled upon a 1.56-mm four-layer PCB having dimensions $40 \times 30 \times 10$ mm$^3$. All signal interfaces are accessible through AMP Micro-MaTch connectors that provide relatively high tolerance for abuse. Battery connections are made via latching JST PA connectors to prevent accidental disconnection during movement. Optionally, completed modules are coated in acrylic varnish to improve resistance to rough handling.

### *Software Specification of MIMATE*

The design of the MIMATE firmware was conducted using Microchip MPLAB IDE/C18. The firmware is based around high- and low-priority interrupt-driven loops to maintain a reliable sampling rate (10–200 Hz) for acquisition of analog signals and inertial measurements and coordinate lower-priority functions, respectively. External control of the module's various data-acquisition and actuator outputs is provided via single-byte instructions sent in a 4-b address/4-b data format via the Bluetooth serial interface. The adjustable parameters include the rate and selection of analog digital converter (ADC) and inertial sensor channels, brightness of onboard LEDs, frequency and intensity of sounder/vibrator output as well as control of the GPIO and serial ports. Acquired data are also returned to the module host by Bluetooth, transmitted as a serial frame containing a header, bit-packed sensor, and ADC samples as well as a time stamp and checksum byte. This generic firmware design reduces the need for (re)programming of the module to accommodate for the requirements of different applications.

MIMATE typically communicates as a slave device over a serial port profile Bluetooth connection with a host PC or other device. To improve the usability of the module, the bit-level functions involved in the communication with the module over the link are encapsulated in a C++ class utilizing standard Win32 application–program interface function calls. This object provides a reduced number of simple, high-level methods and variables (Figure 3) to obtain sensor measurements, configure the device, and control the status of its outputs. This programming approach abstracts the low-level interfacing with the MIMATE and simplifies its application by those with limited experience of C++, helping to ensure accessibility by students with varying backgrounds and levels of skill in software development. The MIMATE class and its use are introduced in a practical session prior to the main lab sessions of H-CARD as described in the next section.

Although the focus of software development in the H-CARD course is primarily on C++, wrappers have been developed for a number of alternative platforms, including National Instruments Labview, Microsoft XNA, the open-source game-development system Scirra Construct, and the Android operating system. This allows for the use of alternative development environments depending on the skill sets of individual students.

## H-CARD Course

H-CARD is a 30-h ($10 \times 3$-h) weekly course in which students from engineering, computer science, and medical backgrounds are taught the practical mechanical, electrical, and software-development skills required for the design and implementation of systems for rehabilitation systems and assistance. Students are encouraged to consider the particular human factors design requirements for these systems, and to develop team-work and project-planning skills for devising a working prototype over a short time. In addition to the primary facilitating platform of MIMATE, students are encouraged to consider the adoption of academically atypical methods to shorten development times and produce a compelling prototype. Examples of such techniques include physically testing designs using materials such as wood, Lego parts, and cardboard; the adoption of techniques from games design; and the adaptation and cannibalization of commodity hardware. The importance of the written coursework is deemphasized during the course with respect to successful production of a well-designed working prototype.

Students for H-CARD are recruited from several departments across Imperial College London (electronic engineering, mechanical engineering, and bioengineering as well as computer science and medicine) and are assumed to have the basic skills in physics and mathematics appropriate for third-year undergraduates in their particular discipline. The course starts with a series of lectures by invited experts on various chronic pathologies commonly responsible for physical disability. Examples of typical pathologies introduced by these talks include epilepsy, stroke, traumatic brain injury, and CP. Focus throughout the lectures is given to typical physical symptoms and disabilities that occur as a result of these conditions, and their rehabilitation. Following these pathology lectures, the students are primed on quantitative means of clinical assessment, basic techniques in human-centered mechatronic design, and the use of electrical sensors and actuators for measurement of aspects of human movement. The lectures concentrate on the use of these design methods in real-world human-centered applications and aim to provide the students with a toolbox of solutions to the engineering problems they will encounter in the course. Each lecture is accompanied by a list of sources for further information that may be used at each student's discretion, should deeper understanding of a topic be required. Following the initial lectures, a four-page individual assignment is set, allowing the students to demonstrate their understanding of the lecture topics (counting for 20% of the final mark): one page to describe a mechanical mechanism of their choice, one page for a selected sensor, and two pages for a selected pathology.

The lecture series is followed by a (2-h) lab session formally introducing the MIMATE module and the basic programming concepts required for its deployment. In this session, the concept of the MIMATE as a prototyping platform is introduced and its basic features and interfaces are described. The students are then divided into groups of four to five and provided with MIMATE and a development PC loaded with Microsoft Visual C++. The remainder of the session consists of several simple software-development exercises of increasing difficulty, designed to gradually introduce the module's capability. These exercises range from a guided tutorial in starting a simple C++ project and including the relevant libraries for the MIMATE, to an unassisted task to measure the module's orientation using accelerometer measurements and provide feedback via light color and intensity. Teaching assistants are on hand at all times throughout these exercises to provide assistance and example code if required.

The main part of the course consists of the practical sessions (15 h) during which students develop a prototype system for rehabilitation or assistance. The fundamentally practical basis of the course and its importance to the students' assessment are introduced from the very start of the course, and students are encouraged to formulate their own ideas for rehabilitative or assistive solutions prior to this point. During the final lecture session, the students are divided into groups with the aim of maintaining as diverse a skill set as possible. The members of each group are allowed to discuss their ideas for a period together and then with the course instructors, aiming to choose an idea to pursue for the remainder of the course and planning its implementation. Prior to the MIMATE introduction session, each group has to give a short presentation on its intended project to the class and receive feedback on the design.

The MIMATE module is used as the core of each project, with standard tools, instrumentation, sensors, and engineering materials available as required. Any special material requirements are discussed at this point and orders are placed. The students are advised to design systems without actuators, thus based on sensing and feedback, due to the rich possibilities offered by such systems and the danger of spending too much time on the motor control. The remainder of the course consists of lab and workshop sessions where the students implement their solutions. A typical session starts with a short classroom meeting where progress is discussed, individual tasks are assigned, and any problems with the project are addressed with the instructors. The class then moves to the lab and practical work commences under supervision. During this phase students are encouraged to work on their projects outside the set hours of the course if necessary, and the lab is made available to facilitate this.

The course is concluded by an assessment of the developed systems (counting for 50% of the course mark, one mark by project's group) during a competition where a short presentation is given by each group followed by a hands-on demonstration session of the projects. Projects are assessed in terms of the therapeutic relevance of the chosen design as well as of its implementation by a panel of invited rehabilitation and human-centered technology experts. Nonspecialist guests and the students themselves are also invited to assess the projects and their marks are combined with the judges' at a reduced weighting. These competition marks are also used during the final to decide the overall winner of the event, who is presented with the course trophy. The session closes with a feedback segment where each judge comments on the projects and answers questions from the students. A full group project report and individual short report on another project is provided a week after the competition and accounts for the remaining marks (30%).

### *Overview of H-CARD Projects*

An overview of selected devices developed by the students over the two years of the H-CARD course is given below to give an impression of the types and quality of solutions produced by the students. The three projects presented showcase the capabilities of the MIMATE module as well as types of devices envisaged by the students.

#### "Piano"

This project aims at improving hand strength as well as finger coordination and independence in chronic stroke patients. The device consists of two "piano"-like keyboards with five color-coded keys, one for each finger of the hand (Figure 4). Each key is hinged against a supporting frame and is capable of sensing pressure via an FSR connected to one of two MIMATE modules. Variable resistance is provided for each key by a replaceable spring. The two keyboards are attached to a supporting board using Velcro, allowing for adjustment to suit the user. A host PC ran an OpenGL-based paint by numbers game implemented by the students using C++, glut, and the supplied MIMATE class. By applying specified levels of force on the correspondingly colored

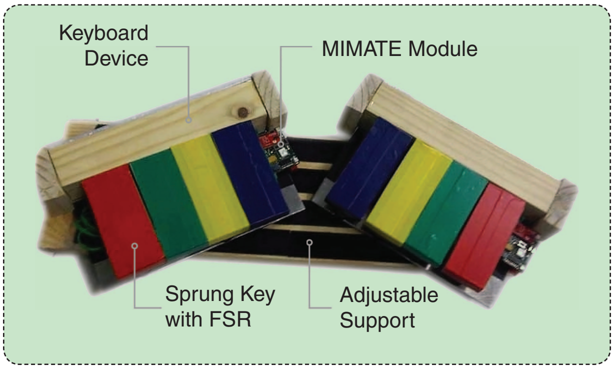



**FIGURE 4** Rehabilitative "piano" interface designed using two MIMATE modules. The user can select colors and create a virtual painting by applying different levels of finger pressure to the sprung keys. The keyboards may be repositioned for user comfort.

keys, the individual colors in a simple picture are produced. Different levels of difficulty are obtained by changing the level and accuracy of force production required from the user as well as requiring combinations of keys to be pressed to produce secondary colors. A score is provided to the user by a number of stars awarded for the successful completion of each picture.

### "The Awesome Game"

Training the ability to stand in cerebral palsy children is the aim of this system in which an interface resembling a scooter is used to control several simple video games (Figure 5). These games aim to exercising the lower legs and progress is achieved by timed flexion of the ankle. The measurement of user posture is achieved through strapping attached to each foot, which integrates a MIMATE module with a flex sensor and FSR. The yaw motions of the handlebars are also measured via a potentiometer. These signals are used to control the position and velocity of a character on the screen in three simple but attractive games. Varying levels of difficulty are provided by increasing the rate and range of ankle flexion required to achieve each game's goal. The development of the software was conducted in the open-source game-development kit Construct, with interface to the MIMATE module achieved by a wrapper for the C++ class to the Construct plug-in SDK.

### "Mushroom Muncher"

The created device comprises a motion-sensing game interface designed to improve wrist strength and control in chronic stroke patients. The hardware consists of an aluminium frame and wrist support with a spherical manipulandum at its center containing a MIMATE module (Figure 6). The sphere is supported via four elastic cords whose tension can be varied to increase resistance to the user. A two-axis proportional interface is provided using the MIMATE's inertial sensor as an inclinometer, by placing the hand upon the sphere and tilting it in the horizontal plane. A third control axis is provided by a proximity sensor attached to the underside of the sphere that measures the distance to the supporting surface. These inputs are used to control a simple Pac-Man-type game on the host PC implemented in C++ and OpenGL. By manipulating the sphere, the user can move a character around the screen with the aim of collecting mushroom-shaped icons and avoiding monsters. When all the mushrooms on the screen at the current level are collected, a new playfield is presented containing more monsters. As a defensive measure, the user can push down on the sphere to deploy a shield to deflect the monsters. Variable difficulty is implemented by varying a combination of the monsters' speed, number of monsters, shield duration, and control sensitivity.

## *Benefits of the H-CARD/MIMATE Course Model*

To our knowledge, the H-CARD course is the first of its kind to teach design considering mechatronics, neuro-rehabilitation, and gamelike training aspects. Over the two years H-CARD has been run, all eight student groups have been able to successfully demonstrate a working prototype in the final competition. This is remarkable, given the difficulties typically encountered with practical mechatronic projects and their live demonstration. Beyond this, the visitors to the competition typically described the projects as "enjoyable to use" and "professionally executed," with all demonstrations being well attended during the hands-on sessions.

Typical criticisms of the projects have concerned the lack of prior evidence for therapeutic gains via the methods employed by the students, or their practical usefulness by severely disabled users. However, the intention of the course is to teach the techniques required for design of rehabilitative or assistive devices rather than to produce complete, practical solutions. Therefore, although a clinically well-supported project concept is desirable, it is by no means essential to the course. Besides consistently high project quality the H-CARD course has also received praise from visitors and positive feedback from students. For both years, the College's internal student feedback was better than the feedback for most courses, with an average of 65% good or very good responses from students across all questions (Figure 7). Some negative feedback was obtained regarding the organization of the course, necessarily relaxed to encourage improvisation, which may not have been appreciated by students accustomed to strongly directed teaching methods.

It has been noted that the regular meetings during the practical section of the course allow students to break down their project into subtasks and assign these to individual group members. These subtasks typically result in smaller investigations (e.g., connect and calibrate a sensor or develop a rehabilitative game) and encourage the students to develop a better grasp of concepts when introduced in the context of the major project. Besides providing the students with the experience of practical project planning, having this clear aim appears to motivate the students to solve the problems they encounter directly, and it encourages spontaneous discussion with their peers when progress falters. It appears from the comments provided by the students and the instructor's experience of the course that the practical aspects of the course are greatly appreciated by the students. In addition to being a primer in more advanced topics in mechatronics, such as control, signal processing, and embedded systems, the lower-level skills taught by the course seem to be greatly valued by the students. Many of them have expressed the opinion that the basic tool use and electronic/mechanical assembly skills they learned as part of


FIGURE 5 A participant playing "The Awesome Game" via a scooter controller. Through a number of sensors and the MIMATE, measurements of posture were translated to control a variety of games (see insets).

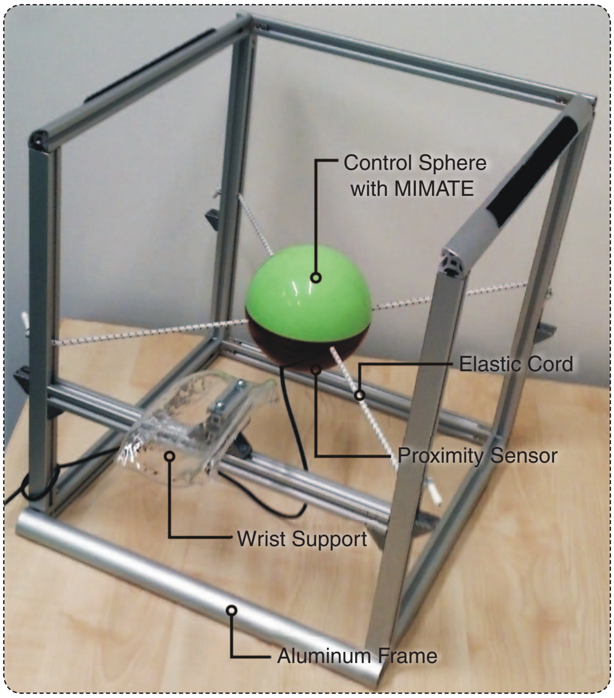



FIGURE 6 The platform device from the "Mushroom Muncher" games. This device consists of a MIMATE instrumented sphere suspended by elastic cords within a frame. By rotating the sphere against the force of the cords, input is provided to a Pac-Man-style game.

H-CARD are essential skills for engineers, yet are neglected in the remainder of their syllabuses.

### Advantages of MIMATE for Education

MIMATE has ensured that groups spend the majority of their time on the design and implementation of a system corresponding to their ideas and focus on the human interaction and therapeutic aspects. The module was well received by the students, particularly during the initial training session where the immediacy of receiving physical feedback from sensor measurements and their software application fostered understanding and inspired further experimentation, often beyond the set assignments. This enthusiasm was also seen during the practical sessions and led a number of students to modify MIMATE and further research the operating principles of its components and the associated sensors or actuators. Negative feedback regarding the device mainly regarded the relatively limited documentation available for the device, which will naturally develop further over time. Students have also suggested that other development platforms are available that might have satisfied the course's equipment requirements (e.g., the Arduino). However, to the authors' knowledge, no commercially available alternative to MIMATE exists that combines the hardware features required by the course, an appropriate form factor, and open compatibility with standard software-development methods.

To reiterate, further testament to the value of the module during the course is the high success rate for the projects as well as the relative quality and compactness of the solutions. These results are remarkable given the limited time scale of the practical sessions. Had off-the-shelf hardware (i.e., discrete data-acquisition devices and sensors) been used, development times would have been considerably longer and the projects considerably larger and less reliable, due to the need to interface multiple sensors, actuators, and data-acquisition systems to achieve a similar measurement or feedback solution. In addition, it is unlikely that solutions would have met size restrictions for use with human subjects and supported wireless, battery-powered operation. An alternative solution would have been the use of commodity hardware, such as a smartphone or Internet tablet, which natively shares a number of sensing and feedback capabilities of MIMATE. However, such devices are typically limited in their capabilities to interface with

| | Very Poor | Poor | Satisfactory | Good | Very Good | No Response |
|---|---|---|---|---|---|---|
| Support Materials Provided | 0% | 8% | 34% | 20% | 37% | 0% |
| Organization of Course | 0% | 23% | 34% | 20% | 23% | 0% |
| Structure of the Lectures | 0% | 1% | 21% | 29% | 42% | 7% |
| Explanation of Concepts | 0% | 1% | 20% | 26% | 44% | 8% |
| Approachability of Lecturers | 0% | 1% | 20% | 23% | 50% | 7% |
| Enthusiasm Generated | 0% | 1% | 21% | 23% | 52% | 4% |

**FIGURE 7** Student feedback from the internal assessment exercise. Percentage responses for the questions provided on the feedback questionnaire are averaged across the two years of the course.

external sensors and actuators. Also, the proprietary software and/or hardware implementations of these consumer devices further restrict their flexibility and hence reduce their usefulness as teaching aids.

## Further Development

Following the initial success of H-CARD, the course will be continued. Plans are in place for the course to be run simultaneously at partner universities, based on the same syllabus and the MIMATE module. This will help to validate the usefulness of the course model and allow for further development and refinement as well as competition between students of these partner universities.

As the limited scope and duration of H-CARD make the complete deployment and testing of a practical rehabilitation device among the clinical population unfeasible, it was not intended that any of the prototypes be directly tested on their intended user base. However, a number of the design concepts devised by the students have been considered to have particular merit by the judges (see the example projects) and could be of possible clinical use. These devices are being explored independently from the course by students engaged in further study or short-term placement. It is intended that these studies will further develop and test these solutions and collect evidence toward publication or application to fund a full clinical study.

The relatively low cost of MIMATE (less than €100 in parts excluding inertial sensor) and its minimal support requirements (a PC accompanied by software available either free of charge or through educational discount schemes) facilitate the teaching of basic concepts of human-centered mechatronic design with a minimum of financial overhead. In addition, each project typically costs less than €200 in hardware. The flexibility of the device and the associated H-CARD model allow it to be used for teaching a range of different disciplines, from high-level development of human–computer interface devices to low-level development of microcontroller firmware. Due to the self-contained nature of the device, it is possible that many of these topics can be taught without the need for a conventional lab or classroom, introducing the potential for asynchronous or distance learning educational paradigms.

As a platform for the development of rehabilitation systems MIMATE offers excellent prospects beyond the educational setting. In particular, due to its portability, cost, and interoperability with commercially available technologies, MIMATE has potential for use in independent decentralized therapy. This would allow for rehabilitative regimes to be continued beyond the clinical setting, potentially improving outcomes and reducing costs of therapy. Furthermore, recent studies have indicated that in some cases passive devices can provide similar advantages as active devices [6]. Examples of such solutions are instrumented objects for training grasping and manipulation, systems to train arm reaching and increase the range of motion, as well as passive aids to improve walking. The characteristics of the MIMATE module make it ideally suited to develop such passive devices for rehabilitation and sport training.

## Acknowledgments

This work was supported in part by EnVision@Imperial College and the EU-FP7 HUMOUR Project. The authors wish to thank the students who have participated in H-CARD for their enthusiasm and perseverance in completing their projects.

***Nick Roach (n.roach@imperial.ac.uk), Asif Hussain (asif.hussain09@imperial.ac.uk),*** *and* ***Etienne Burdet (eburdet@imperial.ac.uk)*** *are with the Department of Bioengineering, Imperial College London, United Kingdom.*

## References

[1] S. Balasubramanian, J. Klein, E. Burdet, "Robot-assisted rehabilitation of hand function," *Current Opinion Neurol.*, vol. 23, no. 6, pp. 661–670, 2010.

[2] L. Deslauriers, E. Schelew, and C. Wieman, "Improved learning in a large-enrollment physics class," *Science*, vol. 332, no. 6031, pp. 862–864, 2011.

[3] P. C. Blumenfeld, E. Soloway, R. W. Marx, J. S. Krajcik, M. Guzdial, and A. Palincsar, "Motivating project-based learning: Sustaining the doing, supporting the learning," *Educ. Psychol.*, vol. 26, no. 3–4, pp. 369–398, 1991.

[4] J. Gindling, A. Ioannidou, J. Loh, O. Lokkebo, and A. Repenning, "LEGOsheets: A rule-based programming, simulation and manipulation environment for the LEGO Programmable Brick," in *Proc. 11th IEEE Int. Symp. Visual Languages*, 1995, pp. 172–179.

[5] A. M. Okamura, C. Richard, and M. R. Cutkosky, "Feeling is believing: Using a force-feedback joystick to teach dynamic systems," *J. Eng. Educ.*, vol. 91, no. 3, pp. 345–350, 2002.

[6] A. Melendez-Calderon, L. Masia, R. Gassert, G. Sandini, and E. Burdet, "Force field adaptation can be learned using vision in the absence of proprioceptive error," *IEEE Trans. Neural Syst. Rehab. Eng.*, vol. 19, no. 3, pp. 298–306, 2011.