Prototyping Potential Control Systems to Assist Complete Quadriplegics

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Why I Wrote This Booklet

When I was in Grade 9 at Ogilvie High School I heard about a complete quadriplegic who had problems controlling his wheelchair. I started a project to see if I could use LEGO MindStorms NXT to prototype a system that could allow compete quadriplegics who have no control of their bodies below their neck, to be able to control their wheelchairs, giving them some independence from their carers.

By about half-way through Grade 10 things seemed to be working, and a teacher suggested that I should write it up and apply for the CSIRO's highest School award, the Gold CREST. To do this, I had to get an expert to say that my project was not rubbish.

I approached the Mechatronics lecturer at the Tasmanian University to see if he thought my project and write-up was any good. He was kind enough to look at it, and must have approved it, as later I was delighted to be awarded a Gold CREST.

However he also said there were some unusual things about my project, and I should think about putting a paper together for a Biomedical Conference that was closing for papers in 10 days.

I asked Mum (Ying Chen) for help, and we squeezed my 60 page Gold CREST report into the 5-page IEEE Conference format just in time. I sent it away without much hope.

Well, I should have had more faith in my work, as our paper was accepted! I had to ask for leave from my Grade 10 class to present my paper at the 5th Biomedical Engineering International Conference in Ubon Ratchathani in Thailand.

This Booklet is based on that paper.

Why you Should Read This Booklet

A conference paper is not available in the usual places that Students and Teachers look for inspiration for LEGO projects. I have now finished my International Baccalaureate studies, and I have time to see if I can put my conference paper into a ".pdf" format, in the hope that this will make it more widely available.

I hope that this write-up will inspire students to work hard and invent marvelous things using LEGO Robotics – believe me, it is a lot of fun!

If after reading this, you are interested in finding out more about my robotics, you can see some videos about my Wheelchair prototype at:

http://www.yayalu.net/YayaLu2011/YayaLu11.htm

and

http://www.yayalu.net/Yaya-Lu-2012/Yaya-Lu-2012.htm

My web site videos also explain my project is less technical language than we have had to use in my conference paper. Enjoy!

ABSTRACT

This paper discusses a versatile wheelchair control system of potential use to complete quadriplegics.

This system employs plug-in components using a common control protocol between the distributed computers.

Two headset plug-in units have been developed together with two prototype wheelchairs and an automatic shopping trolley.

The trolley would be of most use to a paraplegic, but suggestions are made to show how this could potentially be developed to plug into the control system as a type of "personal assistant".

The system has been prototyped using language-independent commands so that it can potentially be used by quadriplegics speaking any of the approximately 7,000 languages spoken on Earth.

LEGO MindStorms NXT equipment has been used to prototype this system.

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Chapter 1. INTRODUCTION

Complete quadriplegics are people who have breaks in their spinal columns above the C7 vertebra [1] and "having no voluntary motor or conscious sensory function below the injury site" [2] are only able to move their head. They are consequently confined to wheelchairs in order to get around, mostly with the assistance of other human beings.

There have been many attempts to help these people by focusing on developing wheelchair devices.

One project involved using a magnet glued to the quadriplegic's tongue to determine the movement of the wheelchair in relation to the direction the tongue is moving [3], while others involved mouth-controlled joysticks [4][5]. These could be inconvenient for the quadriplegics, causing restrictions when eating or talking. Magnets can cause problems if more than one is accidentally swallowed [6].

Voice recognition is a common method for wheelchair control. Either a powerful computer or continuous reliable internet access is required for the voice recognition software to work effectively [7] [8] [9]. Voice control without internet access is a good idea in theory, however if no internet connection is available, educating the software to cope with every individual person's language, accent and word preference can be quite fiddly and time-consuming (and in some cases, quite expensive) to implement properly.

The electrical signals produced by muscles can be detected by an electromyograph (EMG) and used to control a wheelchair [10] [11] [12].

There have also been projects to control a wheelchair by thought. When humans change their thoughts the change in the electrical signals in the brain can be detected. There are two main implementation methods for this approach. One is using a headset from companies such as Emotiv [13] and the other involves surgically implanting a sensor on to the surface of the human brain itself.

The Emotiv headset is a portable electroencephalograph (EEG) that picks up electrical signals from the surface of the head. This signal is complex and reliability is further complicated by the fact that a person's thoughts can be easily distracted. This complexity limits the number of reliably useful commands for wheelchair controls, two or three commands being the limit often reported [14] [15] [16].

A recent report shows a woman controlling a robotic arm to allow her to drink coffee through a straw from a thermos [17]. The arm was controlled by thought alone, using an implant that had been surgically placed directly on the surface of her brain some 5 years earlier. While the future possibilities of this approach would seem large, the training time and expense involved would appear to limit this option for wider application. This subject had head movements, and perhaps less expensive options could also have been possible.

Felzer & Freisleben [10] commented that the EEG command recognition rate (70%) and the slow recognition time make these systems "totally unacceptable for practical ... applications" involving moving users. They commented that voice control systems do not allow conversation while the chair is being controlled, that EMG signals are falsified if the chair travels over bumps, and that if traditional joysticks could be used, they would allow faster point-to-point wheelchair travel.

The authors of this paper wanted to investigate a wheelchair control system that addresses some of the issues raised in the existing approaches mentioned above. We wanted the final product to meet the criteria of being user-friendly, inexpensive, non-intrusive, easy and quick to implement and to be language independent so that a complete quadriplegic speaking any of the 7,000 or so languages used on Earth could adopt it.

CHAPTER 2. METHOD

Two input control systems, two wheelchairs, and a shopping trolley were prototyped (Fig. 1). The system's distributed computer layout allows for easy future expansion indicated by dotted outlines.

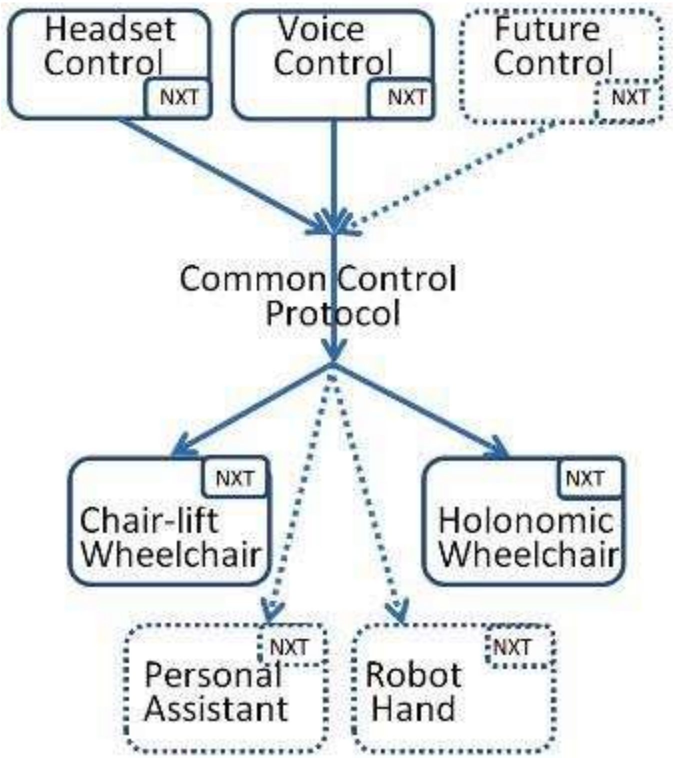

Fig.1 Plug-in wheelchair control system.

2.1. HEAD MOVEMENTS CONTROL PROTOTYPE PLUG-IN.

In this prototype, eyebrows, nose and ears were possible sensor targets. Eyebrows could be independently controlled, and could be used for wheelchair control. LEGO light sensors could be used for detecting eyebrow movements for people with dark eyebrows. Distance-measuring Electro Optical Proximity Detectors (EOPD) sensors from HiTechnic [18] could be used to measure changes in position of fair, bushy eyebrows.

Some people can move their ears. The movement can be small (about 5mm) but distinct enough for a distance-measuring EOPD sensor to detect and use as a command.

Nostril movements were also considered. The original intention was to measure nostril dilation; however it was found that the indent above the nostril showed a greater movement. An EOPD sensor was used, but it only worked marginally well, as the movement of the nose surface was quite small. Figure 2 shows the system with LEGO sensors taking facial movements as commands to control a prototype wheelchair.

Fig. 2: Prototype wheelchair control with head movements.

The exclusion of mouth and chin areas was deliberate to avoid interfering with the quadriplegic's eating or speaking.

Testing of the system on volunteers showed that these chosen head movements can be mastered with practice. We could not find any evidence of pure genetic inheritance of these traits on the internet, so these movements could be considered latent, but trainable.

2.2. Sound Control Prototype Plug-in

A sound control system could be used if a quadriplegic has limited facial or head movements. The preferred voice control system had to be easy for the quadriplegic to use and calibrate, and hopefully easy for Y.L. to implement.

Typical internet-independent voice recognition systems available nowadays are complex to program due to variations of languages, accents, and personal idiosyncrasies creating challenges for recognition. A universal voice control system could be an innovative and attractive alternative option.

A program was written to test the functionality using a LEGO Sound Sensor, to see if long and short sounds could be accurately distinguished. This was tested with multiple people to ensure its reliability and accuracy. It worked.

Morse Code was investigated. It used sequences of dots and dashes to represent letters (Fig.3). Its varying command lengths proved a problem, and an additional challenge for quadriplegic use lies in the exact reproduction of the three different exactly delineated wait times between commands. Our experiments implementing the Morse Code showed that this required signal precision made using it impractical in practice.

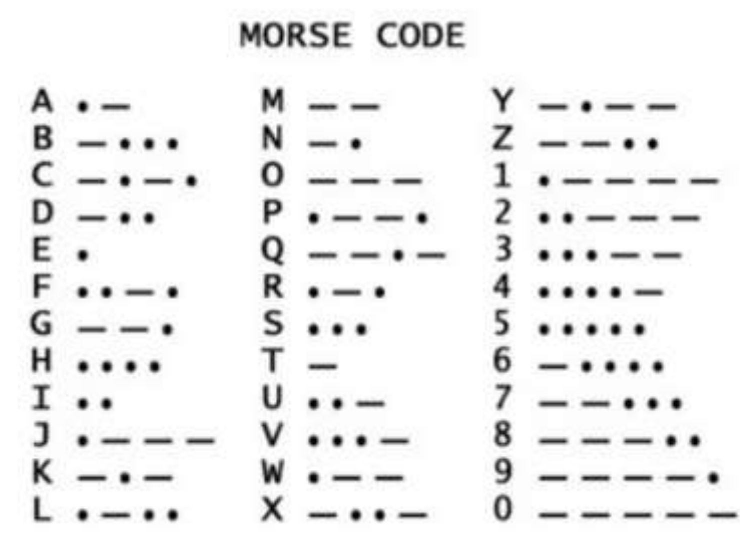

Fig. 3: Morse Code.

The Chinese Telegraph System (Fig. 4) was investigated. This code had a set number of commands (code book page number, row number, column number) per character. This meant there were no varying lengths of codes, and so there was an obvious place where the command would end.

Fig. 4: Portion of a Chinese Telegraph System page.

The ideas behind the Morse Code and the Chinese Telegraph System were combined to create a code which used a fixed number of long and short sounds to represent different commands. This provides a universal method of control.

Using 3 short and long sound commands (hereafter known as “Dits” and “Dahs”) per sequence creates a total of eight unique commands including sideways left and right, which are rarely possible in conventional wheelchairs (Table 1).

Table 1: Command sound signals.

Signal	Command	Control Protocol
Dah Dah Dah	Go Forwards	F
Dah Dit Dit	**Left** Turn	A
Dah Dah Dit	**Left** Sideways	L
Dit Dit **Dah**	Turn **Right**	C
Dit **Dah Dah**	Sideways **Right**	R
Dit **Dah** Dit	Go **Back**wards	B
Dit Dit Dit	Immediate Stop	S
Dah *Dit* ***Dah***	Spare Command	-

This system is versatile, and could be easily adapted for ANY command signal that can be short or long (e.g. head rolls, eye blinks etc.).

2.3. WHEELCHAIR PLUG-INS

Two wheelchair prototypes, one featuring a chair-lift (Fig. 2) and one using holonomic wheels [19] to enable sideways movements (Fig. 5), were built to test this system concept.

Fig. 5: A holonomic wheelchair prototype.

2.4. Radio Signals for Common Control Protocol

The head movements detected by the Headset Plug-in, and the three-sound sequences detected by the Voice Plug-in were then translated into the control protocol codes by their local NXT computer bricks. These control codes were needed by the wheelchair computers for processing into wheelchair movements. Since cables directly linking the headset to the wheelchair would be very restricting, the head and voice plug-ins were sent to the wheelchairs using NXTBee Pro radio links. The common control characters were then translated by the wheelchair's NXT computer program into forwards, backwards, left or right movements for the wheelchair.

2.5. Prototype Personal Assistant

A LEGO shopping trolley, or potential "personal assistant" was also designed and prototyped to autonomously follow a wheelchair around in the supermarket (Fig. 6). This would be better suited for a paraplegic than a quadriplegic. But a robotic arm could in the future be added to this trolley to transform it into a "personal assistant", with the capability of (e.g.) grabbing and lifting objects, switching services on and off.

Fig. 6: A shopping trolley prototype.

2.6. *Safety Considerations*

The command “Dit Dit Dit”, which took the least time to speak, was used for immediate stops. It would also be possible to use face movements (e.g. an eyebrow raise or head roll) to toggle the voice control system on and off.

An automatic warning system was also prototyped, to detect sudden drops in the pavement, or obstacles behind the wheelchair. The idea was to stop the wheelchair, give a warning signal, and move away in order to avoid the obstacle/cliff. These worked well, and could be extended quite inexpensively to all sides of the wheelchair in the future.

2.7. *Personal Considerations*

To allow a paraplegic to reach higher shelves in the supermarket, a chair-lifting device was added onto the wheelchair. This also aims to provide the often-requested ability for a quadriplegic to talk to others at eye-level.

An on/off switch (e.g. actuated by a head roll) could be added to enable speech while the wheelchair is moving.

2.8. *Future Headset Sensor Placements*

Fig. 7: Glasses with sensors.

The sensors which come with the NXT set are quite large, but the electronic components inside are relatively small. In the future, the components could be fitted into a pair of thick-rimmed glasses, rather than onto a headset (Fig. 7).

2.9. *Prototype System Costs*

These systems are relatively inexpensive, costing a few hundred dollars to buy a LEGO Mindstorms NXT set. In the future it may be possible to use even less expensive processors such as the Raspberry Pi [20] or Arduino [21], providing a more affordable control option for quadriplegic wheelchair control systems than other methods that either require a powerful computer processor or physically intrusive devices

CHAPTER 3. RESULTS

The experiments obtained good results in each of three areas. They did this by demonstrating through the use of prototypes that:

- Control of a wheelchair by a complete quadriplegic would be possible if existing movable features of the head were used;
- Control of a wheelchair by a complete quadriplegic would be possible using a short sequence of sounds of varying length;
- An automatic wheelchair-following shopping trolley for use by a paraplegic would be feasible.

Regarding future work, an attached robot arm could be built to enable the conversion of the "trolley" into a "personal assistant" (Fig. 6) controlled by the complete quadriplegic. The same control system could potentially be switched between these devices, allowing a complete quadriplegic to control all three devices (wheelchair, personal assistant, robot arm) using a similar set of commands to save re-learning the commands. Only one device would be controlled at a time.

CHAPTER 4. DISCUSSION

4.1. Choice of Materials to Build the Prototypes

The prototypes were built using LEGO Mindstorms NXT sets that are quite inexpensive compared to some of the wheelchairs designed specifically for quadriplegics today [22]. Previous experience [23] with the LEGO NXT MindStorms set established it as versatile prototyping system. Y.L. has had experience with several NXT languages and chose to use RobotC because it is the fastest NXT language [24] with the best debugging facilities.

4.2. Choice of Sensors for Headset Plug-in.

After much experimentation, it was decided that the LEGO light sensors could be used for detecting eyebrow movements for people with dark eyebrows. Distance-measuring HiTechnic EOPD sensors could be used to measure changes in position of fair, bushy eyebrows, and could also be successfully used to detect ear movements. An EOPD sensor was also used to measure nose dilation, but it only worked marginally well, as the movement of the nose surface was quite small (Fig. 1). Eye areas were intentionally excluded to avoid possible retinal damage from the infrared sensors.

A major problem with using the NXT LEGO light sensor was that it is very sensitive to changes in ambient light levels. This made a huge difference when we were testing it indoors and then outdoors, day and night, or even in shadows. By contrast, the HiTechnic EOPD sensor used pulsed light, and is far less sensitive to variations in ambient light. In the real-life wheelchair, the sensor needs to be sensitive enough so that the quadriplegic's movements can be detected, but not so sensitive that its reliability would be compromised by moving between different geographic locations.

Not many humans have developed the ability to move their ears, but it seems to be a latent ability. The muscles and nerves are present in humans, and we could find no evidence of major genetic variations that affected only this ability. We feel that this type of control could be achievable with practice.

Even though the sensors that come with the NXT set are quite large, the electronic components inside are relatively small. Consequently, a real system could be implemented with the electronic components built into a pair of thick-rimmed glasses (Fig. 7), rather than onto a separate headset.

4.3. VOICE CONTROL SYSTEM PLUG-IN

A voice control system is an alternative solution if the quadriplegic was unable to move areas of the head. Typical voice recognition systems available nowadays are mostly language dependent which limits adoption by minority populations. They are also complex to program due to varieties of accents and personal idiosyncrasies. A simple universal voice control system is proposed in this paper, using a combination of some of the ideas behind Morse Code and the Chinese Telegraph System to provide a possible solution.

The authors expected to have to calibrate the LEGO sound sensor to deal with different background noise levels. We calibrated this for indoor use, and found that, if the sound sensor was held reasonably close to the mouth, the system responded quite reliably without having to change the initial calibration when moving around the house, even when TV is blaring out at a volume suitable for people in need of hearing aids. We expected to have to calibrate the “dits” and “dahs” individually for each person. However after testing the system with a variety of English and non-English-speaking people, we found that the lengths of the "dits" and "dahs" were surprisingly similar, and that an initial long/short "decision point" built into the software worked for most of the people who tried the system. If necessary, this "decision point" can be easily changed.

4.4. Shopping Trolley Prototype

The prototype automatic shopping trolley worked well. If a full-size system was made, careful adjustment of the way the trolley approached the wheelchair would be necessary.

We used a HiTechnic IRSeeker sensor on the trolley in combination with a HiTechnic Electronic Ball mounted on the wheelchair to reliably find the direction of the wheelchair. This worked well, as long as there was a clear line of sight between the shopping trolley and the wheelchair.

We then tested two sensors in an effort to stop the shopping trolley from banging into the wheelchair.

A touch sensor worked quite reliably, but the touching part of the sensor had to be very carefully placed, otherwise the trolley would hit the wheelchair before the touch sensor was activated. This often happened if the trolley met the wheelchair at an angle.

To attempt to obtain a more reliable approach, we tried a LEGO ultrasonic sensor that detects sound echoes. This has two advantages. The first is that the trolley does not have to bump into the wheelchair, because it can be stopped at a certain distance from the wheelchair. The second is that the speed of the trolley can be decreased as the trolley nears the wheelchair. The only problem with the ultrasonic sensor was that, if the wheelchair was at an angle to the trolley, the reflected sound waves could be weak because most were reflected sideways by the flat surfaces on the wheelchair (Fig. 8).

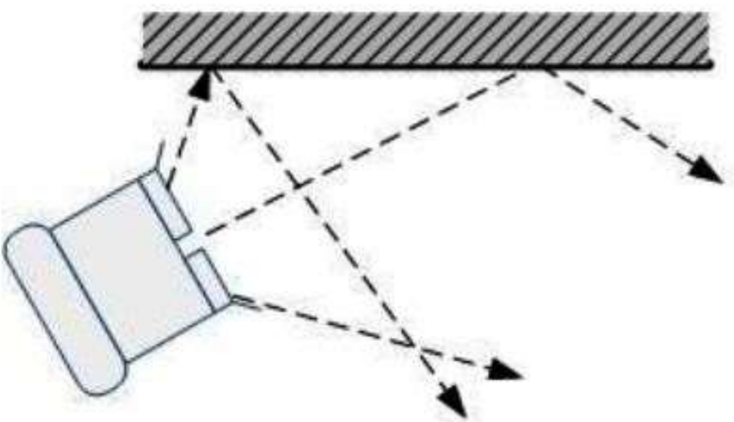

Fig. 8: Ultrasonic sensor signal scatter.

This could be easily fixed in a full-size version of this system if a ridged zig-zag wheelchair outer surface was used.

The automatic shopping trolley would be better suited for a paraplegic than a quadriplegic. But if a robotic arm was added, and the proposed extensions of the wheelchair control system were used to control both the trolley and the robotic arm, the shopping trolley could be converted into a "personal assistant" for a quadriplegic. This "assistant" could (e.g.) obtain items, or switch services on and off, to assist the quadriplegic.

There were problems with the Linear Actuator [25] used to raise the wheelchair's chair; our initial units had manufacturing faults. The manufacturer claims a 1 km. radio range and 65,000 network addresses for the NXTBee Pro. [26], but the battery ran down very quickly (no on/off switch) and the battery connections were fragile. In both cases replacement versions corrected these faults.

4.5. *Conclusion*

We successfully prototyped an easily-extended system using plug-in components that could be of potential assistance to complete quadriplegics. The system currently used both facial movement controls and voice controls to show that it was possible for a complete quadriplegic to control a wheelchair.

For particular quadriplegics, the plug-in design of this wheelchair control system should make it relatively easy to combine additional elements into this system to overcome a particular quadriplegic's individual handicaps.

The automatic shopping trolley could assist a paraplegic; it had the potential (with further work) to act as a "personal assistant" to quadriplegics.

The simple hardware requirements of this system enabled it to be both easily implemented and extended. Most importantly, the control system is language independent, making it a universally adoptable system.

ACKNOWLEDGMENT

We are very grateful for the help provided by Dr. Graeme Faulkner with his RobotC sensor tutorials [27]; his knowledge of robotics and dedicated supervision have highly inspired us.

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About The Author

Yaya is somewhat self-effacing, and she has asked me to write this note. My knowledge of Yaya comes from occasionally acting as her mentor.

Yaya has been playing with Lego robots since before 2006. Since then she has achieved robotics success in State, National and World events, including two World RoboCup Junior Firsts (the Rescue category in Austria and the Dance category in Singapore); first place in the senior category of the Australian RoboGals Competition; the highest Australian School CSIRO award - the Gold CREST; the highest Australian School Science Award - first place in the BHP-Billiton Engineering Award; among 1600 of the brightest students from 72 countries at the International Science and Engineering Fair in Arizona USA she gained a first Citation Award; she was invited to Google’s Australia-New Zealand Anita Borg Scholarship retreat even though she was technically too young; and she gave an oral presentation of her paper at the IEEE Fifth Biomedical International Conference in Thailand.

Outside robotics, Yaya was the Tasmania representative in the Pride of Australia Medal, was a finalist in the Tasmanian division of the Young Australian of the Year, was invited to address the Tasmanian Parliament at their Annual Science Forum, has achieved a 99^{th} percentile in the National Mathematics test; and has won prizes and medals in Piano and Judo when younger.

Yaya has just finished the International Baccalaureate with a score of over 40 points, confirming her eligibility to take up the offer of a five-year Tuckwell Scholarship at the Australian National University in Canberra in 2015, where she is currently a student.

You can find out more about Yaya's Robotics journey at:

http://www.YayaLu.net/Yaya-Lu-2013/Yaya-Lu-2013.htm

In summary, I think Yaya is an excellent example of what a bright student can achieve with hard work, while having a lot of fun in the process.

Graeme.