USING LEGO IN CONTROL EDUCATION

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Abstract: Experiences at Glasgow University in using LEGO Mindstorms for Control Education are described and implementation details given. *Copyright©2006 IFAC.*

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1. INTRODUCTION

The LEGO Mindstorms Robotic Invention System combines simple yet unconstrained construction, servo motors, sensors and embedded programmable microprocessor (the RCX component) with infra-red communications. Although it is marketed as an educational toy for children aged 12 years and over, it has attracted wide interest from adult enthusiasts who have extended both hardware and software (Baum, 2000; Baum *et al.*, 2000). In particular, the Brickos(brickOS, 2004) real-time kernel has been developed.

The RCX component was initially developed as an educational tool through the collaboration of LEGO and MIT (Resnick *et al.*, 1996; Papert, 2000). In particular the education potential of a self-powered mobile system combining easy construction, easy software development built in sensor and actuator interfaces was stressed by Martin (1994). Although the Lego Mindstorms kit provides an easily obtainable integrated system, there are other possibilities as discussed by Martin (2001).

The control community has taken up Lego Mindstorms for engineering education (Heck *et al.*, 2004; Rieber *et al.*, 2004; Gawthrop and McGookin, 2004; Casini *et al.*, 2005). This paper does *not* provide a survey, but rather concentrates on work at Glasgow University on using Lego Mindstorms for engineering education. The discussion is divided into four parts: bench-top demonstrations, laboratories, projects and postgraduate research.

Bench-top demonstrations Because the LEGO Mindstorms kit allows the construction of a preprogrammed autonomous vehicle (no wires) it is particularly suited to creating bench-top demonstrations for motivating lectures. Section 2 provides a detailed account of a simple cart and pendulum system which uses feedback control to move the cart whilst reducing the swing of the pendulum.

Laboratories and Projects The undergraduate teaching programme at Glasgow includes formal laboratory work for robotics teaching and final year projects. These activities utilise the fast development capabilities of the LEGO technical framework coupled with imagination and fun to provide the desired pedagogical outcomes. Section 3 discusses the laboratory component and Section 4 discusses projects.

Postgraduate research LEGO Mindstorms is used at Glasgow for postgraduate robotics research focussing on the design of prototype mobile robots and associated systems. This illustrates the power of

LEGO Mindstorms when combined with advanced programming and circuit design.

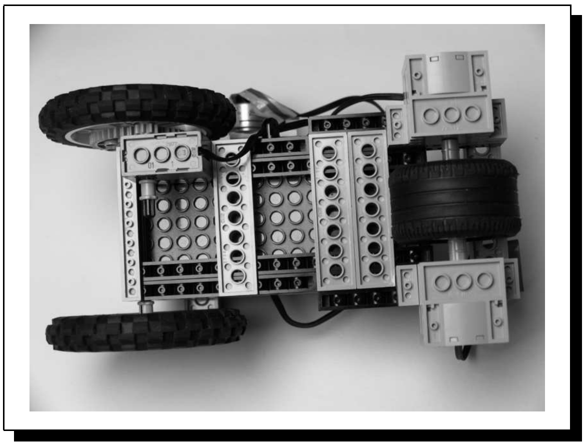
2. BENCH-TOP DEMONSTRATIONS

Fig. 1. Bench-top Demonstration. *The cart (shown in detail in Figure 2 carries a load suspended by the suspension of Figure 3. The purpose of the controller design is to move the cart between two points whilst suppressing the sway of the load.*

In an earlier paper (Gawthrop and McGookin, 2004), the authors described the design and implementation of a pendulum and cart using the LEGO Mindstorms kit for construction and brickOS(brickOS, 2004) (previously called legOS) for control software implementation using techniques described in the books of Baum (2000) and of Baum *et al.* (2000). In particular, the pendulum and cart system provide an ideal bench-top demonstration within the context of an undergraduate course in control systems.

Although LEGO has many convenient features, it has some drawbacks in the context of control system implementation. In particular

1. The pulse-width modulation motor drive (Baum *et al.*, 2000) gives rise to non-linear behaviour.
2. There is no accurate angle sensing device provided.
3. There is no velocity sensing device provided.
4. The supplied software (both kernel and user) is inadequate for control systems work.
5. The use of gearing leads to friction and backlash, particularly under load.



(a) Bottom View

(b) Side View

Fig. 2. Cart Detail. *Figure 2(a) shows the underside of the cart. The two motors at the right-hand side share a shaft with the central driving wheel; one motor is driven, the other acts both as an electrodynamic brake and velocity sensor. Figure 2(b) shows a side view. At the left-hand side, a wheel has been removed to reveal the position sensor; the large gear wheel shares an axle with the removed wheel and drives the LEGO rotation sensor, via the small gearwheel with a 1:5 ratio, to measure horizontal cart position.*

As discussed previously (Gawthrop and McGookin, 2004), item 1 can be overcome by using a motor with short-circuit armature in the drive; item 2 can be overcome by building a special sensor using an instrumentation-quality potentiometer; item 3 can be overcome using a separate motor as a tachometer and item 4 can be overcome using the open-source real-time multi-threaded operating system brickOS (previously called legOS).

This section describes a bench-top pendulum and cart system focusing on the innovations subsequent to the

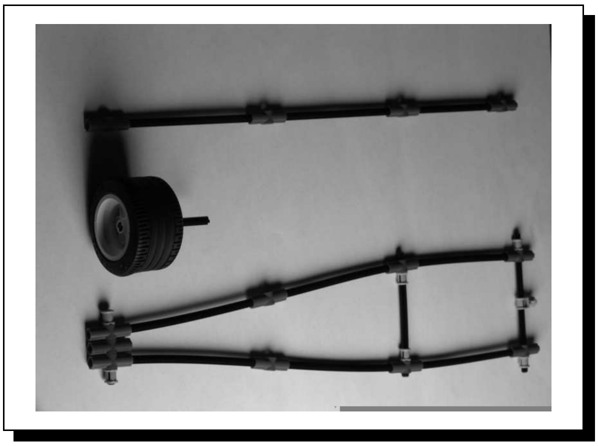


Fig. 3. Load suspension: Detail. *Two versions of the load suspension are shown; the left hand version is simple but exhibits resonance effects whereas the right-hand version avoids this problem. The load is also shown; together with the suspension this forms the pendulum.*

previous work of the authors (Gawthrop and McGookin, 2004).

2.1 Lego construction

Based on our experiences with an early version(Gawthrop and McGookin, 2004), Figures 1, 2 and 3 show our current LEGO design. The angle sensor of (Gawthrop and McGookin, 2004, Figure 2) is reused in this design; the cart position sensor of Figure 2(b) is similar to (Gawthrop and McGookin, 2004, Figure 4b) .

The main mechanical improvements are detailed below.

Drive Because of item 5, the drive visible in Figure 2(a) has no gears; instead two LEGO motors are connected by a shaft that also passes though a wide-tyred drive wheel. One motor is powered from the RCX and the other acts as both an electrodynamic brake and velocity sensor. As discussed previously (Gawthrop and McGookin, 2004, Figure 3b), the use of a brake helps to linearise the effect of item 1; however we no longer use a short circuit to form the brake but rather use a 47Ω resistor instead. The resulting non-zero voltage can then be used for velocity measurement (Gawthrop and McGookin, 2004, Figure 3a).

Suspension A small detail, but which demonstrates the connection between structural and control design, is illustrated in Figure 3. The original (single rod) design was found to exhibit resonances subsequently exited by the control system – see Figure 6(b). Rather than redesign the control system, the suspension was redesigned as in Figure 3; this completely removed the problem – see Figure 6(c).

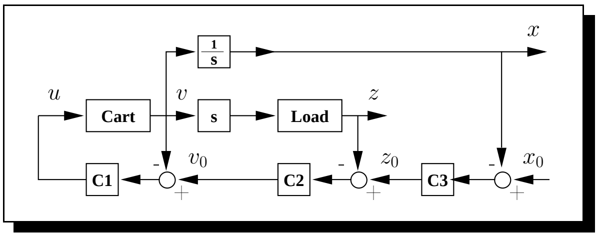


Fig. 4. Control structure. *There are 3 cascaded control loops: **C1** controls cart velocity v, **C2** controls the load position z and **C3** controls cart position x.*

2.2 Control system design

As shown in Figure 4, a three-loop approach is used: the three controllers **C1**, **C2** and **C3** control the cart velocity *v*, the load position *z* and the cart position *x* respectively in a cascade configuration. The two outer loops **C3** and **C2** provide the setpoints for the two inner loops **C2** and **C1** respectively.

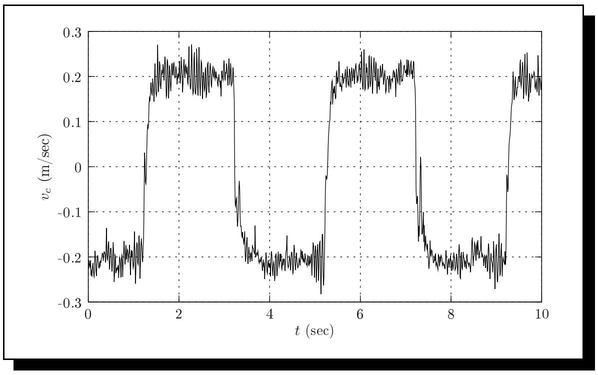


Fig. 5. Inner-loop: cart velocity

2.2.1. Inner-loop: cart velocity (C1)

As noted in Section 2.1, the motor driving the cart axle is directly coupled to the velocity sensor. Because the cart appears to be (approximately) a single integrator at this level, a high-gain proportional controller is used. Figure 5 shows the response of this loop to a square-wave velocity setpoint of $\pm 0.2\mathrm{ms}^{-1}$. The velocity measurement is quite noisy, but otherwise the loop gives tight velocity control with a time constant of about 200ms.

2.2.2. Middle-loop: load position (C3)

A number of authors (including Åström and Furuta (2000)) have shown [1] that the pendulum dynamics of Figure 1 can be described by:

$$J\ddot{\theta} + mgl\sin\theta + ml\cos\theta\dot{v} = 0 \qquad (1)$$

where *J* is the inertia of the pendulum about the pivot, θ is the pendulum angle measured anticlockwise from the downward position, *m* is the pendulum mass *l* is the length of the pendulum from the pivot to the mass centre and *v* the cart velocity. If the suspension is light

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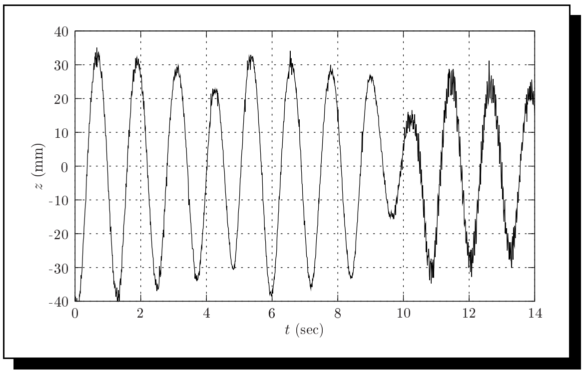
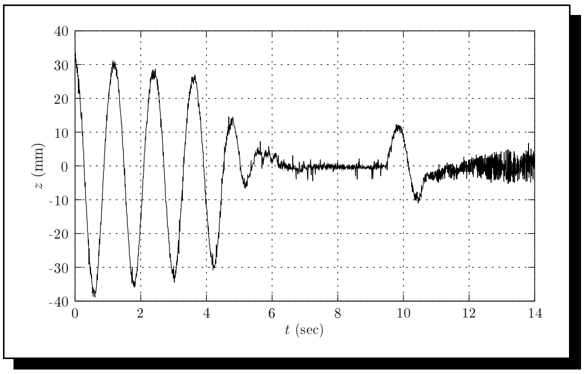
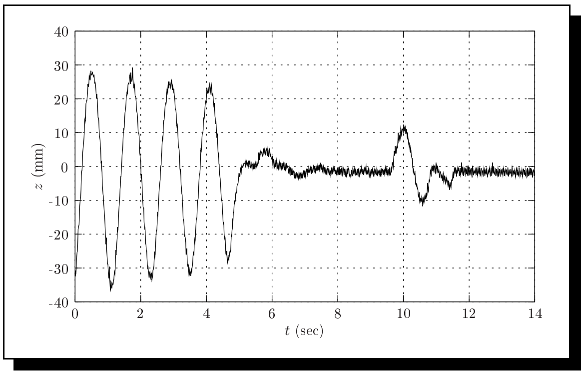
[1] There is a sign change due to our sign convention



(a) Without pendulum control



(b) With pendulum control



(c) With pendulum control (Revised suspension)

Fig. 6. Pendulum displacement z. In each case the control is switched on at time $t = 4$ seconds and the cart position setpoint switches between ±0.1m every 5 seconds. (a) The lightly damped pendulum swings in an uncontrolled fashion. (b) When the control is switched on, the pendulum is rapidly brought to rest; subsequently the pendulum moves slightly at the setpoint change at $t = 9$.(c) The suspension was modified to avoid resonances.

$J = ml^2$; further assuming that θ is small and noting that the load position $z = l \sin\theta$, (1) can be written as:

$$\ddot{z} + \frac{g}{l} z + \dot{v} = 0 \tag{2}$$

Defining the natural frequency ω_n as

$$\omega_n = \sqrt{\frac{g}{l}} \tag{3}$$

and choosing the feedback control

$$\dot{v} = 2\xi\omega_n \dot{z} \tag{4}$$

gives the closed-loop equation for the load position as:

$$\ddot{z} + 2\xi\omega_n \dot{z} + \omega_n^2 z = 0 \tag{5}$$

The damping ratio ξ can be chosen by the designer: $\xi = 1$ (critical damping) is used in the sequel.

Equation (4) can be integrated to give

$$v = 2\xi\omega_n z \tag{6}$$

Equation (6) is further modified by adding a setpoint term z_0 used by the outer loop.

$$v = 2\xi\omega_n z - z_0 \tag{7}$$

*2.2.3. Outer-loop: cart position (**C3**)* The outer-loop controller (**C3**) is a simple proportional controller generating the setpoint z_0 for **C2** by the proportional controller:

$$z_0 = k_{cp}(x_0 - x) \tag{8}$$

Figure 6 shows the load position z, plotted against time, for three cases. It is interesting to note that the pendulum redesign of Figure 3 was needed to avoid suspension resonances.

2.3 Software

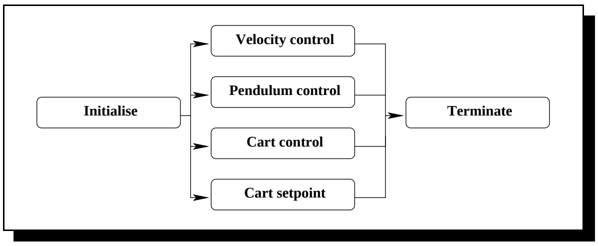


Fig. 7. Software structure. The three controllers **C1**–**C3**, together with a setpoint generator, are each programmed as separate *threads* and thus (conceptually) run in parallel until the terminate signal is received

The (brickOS, 2004) operating system replaces the LEGO-supplied kernel. It is a real-time, multi-threaded, Posix-compliant kernel. Together with a floating-point library and the gcc compiler, it is readily programmed in C++. Figure 7 outlines the software structure and Figure 8 shows some of the corresponding code [2].

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[2] The complete computer code is available from www.??

```
...
tid_t  pa_thread,ref_thread;  /* Thread  ids  */
...
int  pendulum_angle_control(int  argc,  char  **argv){
    double  pp;        /* Pendulum  bob  position  */
    while  (!shutdown_requested())  {
        msleep(DT_pa);

        if  (MODE==2){
            angle  =  pendulum_angle(angle_0);
            pp  =  bob_position(angle);
            cv_r  =  2*ZETA*W0*(pp−pp_r);
        };
    };
    return  0;
};
...
int  main(int  argc,  char  **argv)
{
    initialise();
    /*  Start  the  threads  */
    cv_thread  =  execi(&cart_velocity_control,  ...
    pa_thread  =  execi(&pendulum_angle_control,  ...
    cp_thread  =  execi(&cart_position_control,  ...
    ref_thread  =  execi(&reference,  ...
    /*  Hang  about  */
    while(!shutdown_requested())
        msleep(1000);
    return  0;
};
```

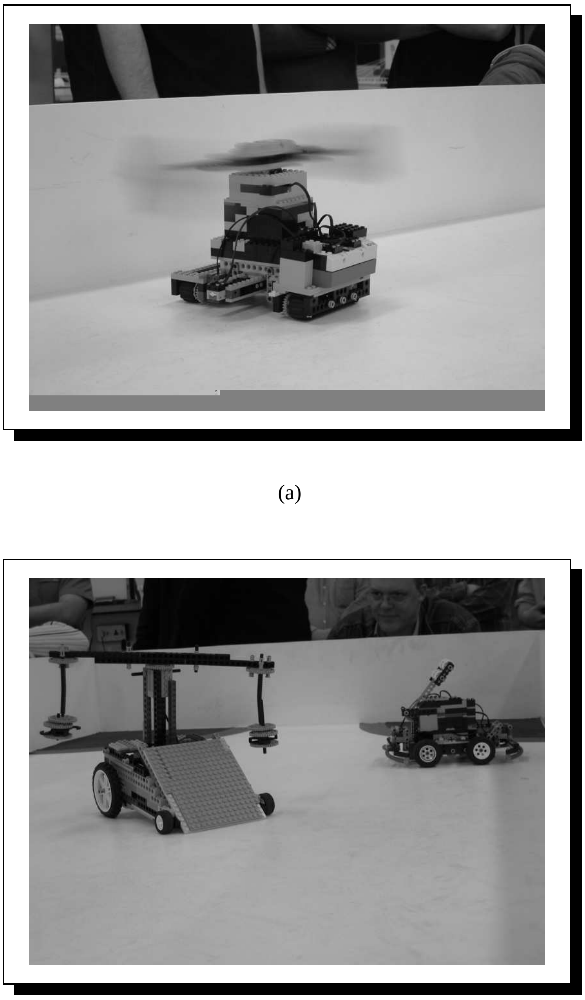
Fig. 8. Code fragment: Thread programming. This code fragment illustrates the code corresponding to Figure reffig:threads. Omitted code is indicated by ...

Both kernel and controller code are loaded into the RCX brick via the USB IR “tower” supplied with LEGO Mindstorms.

3. LABORATORY EXERCISES

The main undergraduate activity that uses LEGO Mindstorms is a construction and programming laboratory exercise for senior honours course on robotics. The lecture material in the course covers the systems and dynamics of industrial robot manipulators. Due to the highly mathematical nature of the course material, the majority of the student cohort finds it difficult to engage with the subject matter. The laboratory exercise has been developed to introduce an element of expressive freedom and fun to balance the teaching experience of the students.

The particular exercise that is popular with the students is a version of Robot Wars (Miles and Carroll, 2002). In this altered version of the competition, the student cohort is organised into teams of 3 or 4. Within these teams the students design, construct and programme robot warrior contestants for a final competition (see Figure 9) for some examples of student designs). This construction process is undertaken during laboratory sessions that run in parallel to the lectures. The easy to assemble LEGO components allow the construction process to be rapid and thus enable the students to have prototype designs developed in a very short period of time. This is essential so that these activities do not distract the students from other course work. Such short lead-time from design concept to final development could not be achieved using traditional construction materials and methods.


(a)

(b)

Fig. 9. Robot Warrior Design. (a) and (b) show different designs buy students

At the end of the course the robot compete in a gladiatorial tournament where the operational performance of the designs are considered and form part of the laboratory assessment (see Figure 10). The other assessment component comes from a formal report and presentation outlining the suitability of the students’ designs for the purpose of the competition. The combination of the laboratory activities and the participation in the final competition provides the necessary enjoyment factor for undergraduate study.

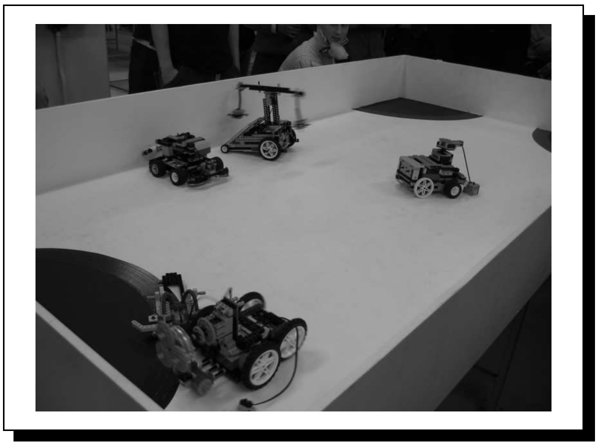


Fig. 10. Robot Wars Style Competition

4. UNDERGRADUATE PROJECTS

An intrinsic part of every undergraduate engineering degree at the University of Glasgow is the final year project. This project forms one of the major practical learning experiences for engineering students as it allows them put theory into practice. However, the students find that they have to manage the time they spend on their projects so that they can accommodate their other studies. This means that students need to use technical materials and components that can produce designs in a very short period of time. Thus LEGO Mindstorms is ideal for this, particularly when designing robotic or autonomous vehicles. Some of the successful robotic design projects that have been carried out within the Centre for System and Control are discussed below.

4.1 LEGO Football

One of the most noted activities for robotic design enthusiasts has been robotic football. Through the RoboCup Junior League (http://www.robocupjunior.org), international competitions have been established that provide a forum for displaying innovative designs for robots and strategies. These events have allowed goal driven cooperative robotics research to be advanced.

The rules for RoboCup Junior Football have formed an international standard for robotic football activities. The rules outline the requirements for the following aspects of the competition (http://www.robocupjunior.org):

(1) Size of the robot - The robot should fit inside a specified dimensional perimeter (i.e. a cylindrical outline, 22cm in diameter and 22cm high).
(2) Dimensions of the playing field - The playing field should be 183cm long, 122cm wide, 14cm high, with two goals at either end that measure 45cm.
(3) Colouration of the playing field - Greyscale going from dark to light from one goal to the other, the walls are painted matt black and the goal area is coloured matt grey.
(4) Ball - A purpose built infrared ball is used, which can be detected by the standard LEGO Mindstorms light sensor.

Apart from these rules, the designers only have the limitations of their own imaginations when it comes to their team design. This has resulted in a number of innovative designs and strategies for robotic systems.

These rules have provided the basis for a number of undergraduate projects in this area. The latest project has involved two students designing, constructing and programming separate teams with two robot players in each (see Figure 11 and http://www.robocupjunior.org).

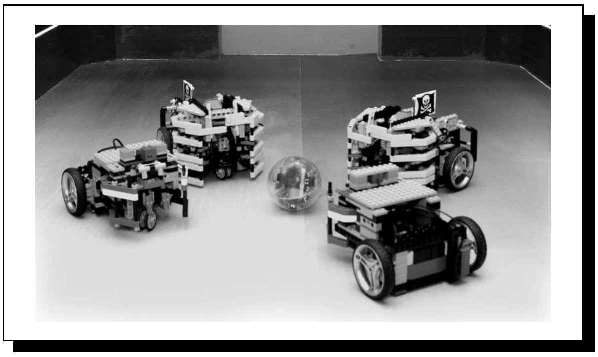


Fig. 11. Football Team Robots on the Playing Field with IR RoboCup Ball

The first team (shown in the foreground of Figure 11) uses conventional motion measurement based on light sensors scanning the greyscale of the playing field. The second team (shown in the background of Figure 11) uses a purpose built compass sensor to direct the motion and strategy for the team members.

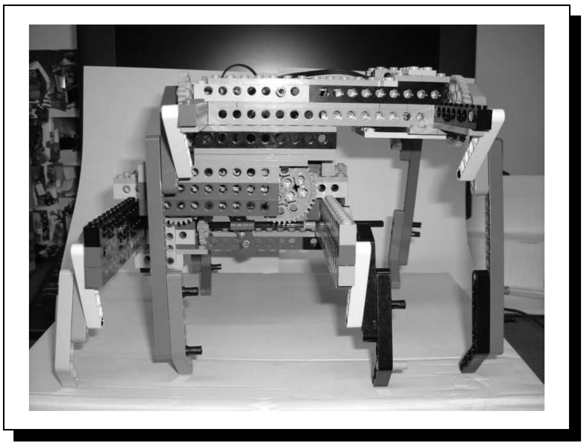
Although the robots have been constructed in different ways and use different ways to determine direction and motion, they have both used BrickOS as the programming language for these systems. The programs themselves reflect the differences in sensor types and the associated strategies for playing football (e.g. defensive).

Overall, the outcomes from the findings of this investigation naturally have shown the benefits for the compass sensor over the light sensor approach. These conclusions have been drawn from a number of matches where the teams have competed against each other. This fun approach to determining the benefits of different sensor approaches for multi-agent systems has relied on the flexibility and diversity that LEGO Mindstorms provides.

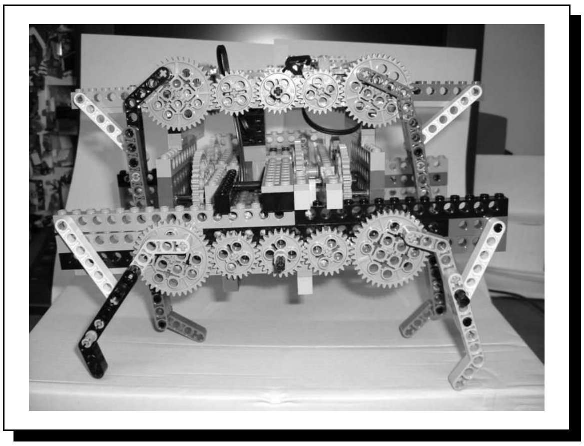
4.2 Walking Robots

Biomimetic robotics is a growing field with many different replicant robot applications of various biological species (Iovine, 1998). The interest for some researchers concerns improvements in propulsion systems for robot designs. These improvements are in terms of speed, stability and navigational performance over rough terrain.

In order to investigate different propulsion mechanisms for walking robots, a project has been undertaking that examined the effect of different leg configurations for walkers (Iovine, 1998). The walking robots have been designed with different numbers of legs and propulsion configurations (Alexander, 2003). These covered bipeds, quadrupeds, hexapods and octopods (see Figure 12 for octopod design).



(a) Front view



(b) Side View

Fig. 12. Walking Robots

These designs have been configured to use the least number of LEGO DC motors and thus reduce the power drain on the batteries. Overall the designs have been rapidly developed using LEGO Mindstorms and, the respective gaits and navigational strategies have been programmed using BrickOS (Alexander, 2003).

The outcome of the investigation showed that the chosen hexapod design exhibits the most manoeuvrability, stability and economic running (in terms of power consumption) of all the designs considered. As with the Robotic Football project, the success of this study has been primarily due to the flexibility and ease of construction that the Mindstorms equipment provides. Also, using BrickOS to code the RCX has shown that much more could be achieved from LEGO Mindstorms based robotic systems.

4.3 *Robotic Fish*

Following the theme of biomimetic robotics, another project that has been undertaken at the University of Glasgow is the development of a robotic fish using LEGO Mindstorms (Miles and Carroll, 2002; Alexander, 2003; Sfakiotakis *et al.*, 1999)(see Figure 13).

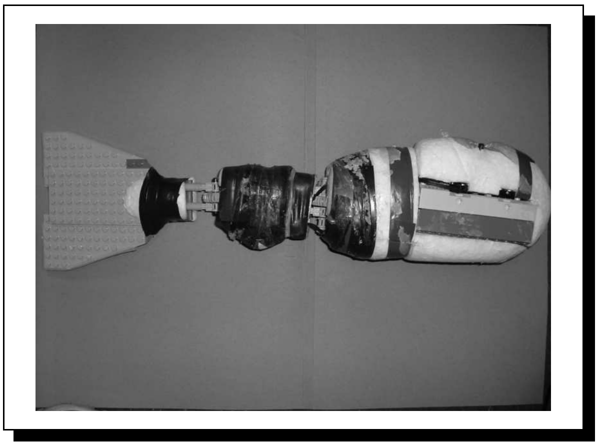


Fig. 13. LEGO Mindstorms Robotic Fish

The design of the fish uses two DC motors to drive the sectional tail. The undulatory motion of the tail then propels the fish through the water (Alexander, 2003; Sfakiotakis *et al.*, 1999). In order to achieve accurate, synchronised positioning of the motors, the position of each section of the tail is measured using a potentiometer. These gives precise measurements of position that are fedback to the RCX so that it can provide the required signals to the motors and thus produce the desired motion of the tail. This motion generates the vortices necessary to produce a propulsion force that is similar to the force produced by a real fish.

The weight of the RCX with batteries has to be counterbalance with some buoyancy aides. In this case the student has used moulded polystyrene to make the fish neutrally buoyant (Alexander, 2003). So that the robot remains watertight the whole fish is covered in a latex skin. This skin ensures that robot’s electrical components remains unaffected by its swimming environment.

This project illustrates that LEGO Mindstorms could be used to design a wide variety of robotic systems and not just mobile robots.

5. RESEARCH PROJECTS

So far it has been shown that LEGO Mindstorms can be used effectively for teaching and project work. Although some of the projects touch on fields of research being currently undertaken at the University of Glasgow, they are not the primary focus for specific research activities. However, one current research project is using LEGO Mindstorms and BrickOS to develop prototype mobile robots.

This particular project is looking at the design and development of mobile robots for Urban Search and Rescue (USR) scenarios (Murphy, 2004). It is foolhardy to believe that LEGO based robots could be used in practice, but this study has started by using LEGO Mindstorms to develop prototype robots (see Figure 14) that are then developed into physical, more robust USR robots.

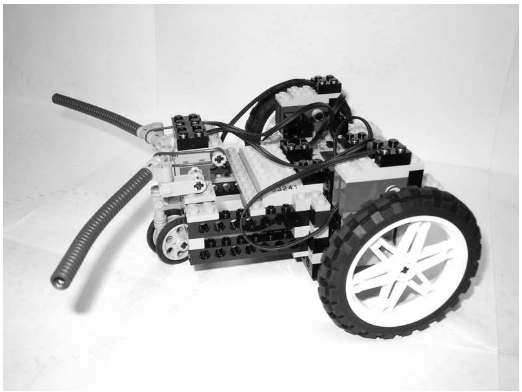


Fig. 14. Initial Mobile Robot Prototype

In order to enhance the performance of these robots, compared with the standard designs achieved with LEGO Mindstorms, a MEMS based Inertial Measurement Unit (IMU) has been developed (http://www.analog.com). This IMU measures motion along the longitudinal and lateral axes of the robot as well as the heading motion of the vehicle. The data from this dual axes IMU is read directly into the RCX, which acts as a data-logger and control processor. Overall, the combination of the IMU, the RCX running BrickOS and the fast prototyping technical LEGO has allowed the researcher on this project to advance the research extremely quickly. Future progress of this project will hinge on the development of these prototypes and the valuable lessons learned from implementing and developing USR robots using LEGO Mindstorms.

6. THE FUTURE

Recent announcements indicate that a new generation (NXT) of LEGO will be available within a few months. Combining bluetooth communication with a 32 bit processor should provide a strong basis for future developments. It is hoped that the open-source community will rise to the challenge.

7. ACKNOWLEDGEMENTS

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