Sensor systems in a compliant geometry robot: ButlerBot.

Stephane Railhet, Joerg Wolf, Amine Adra, Rashad Kabbara, Sarang Deshmukh, Musaab Garghouti, Gregory Nash, Tony Belpaeme, Phil Culverhouse, Paul Robinson, Peter White, Guido Bugmann[1]

School of Computing, Communications and Electronics
University of Plymouth
Drake Circus, Plymouth PL4 8AA, U.K.
gbugmann@plymouth.ac.uk

[1] Corresponding author.

Abstract

Butlerbot is a robot designed to serve drinks at receptions. Due to the expected close proximity between the robot and the users, a new compliant geometry concept has been used, where the body shape of the robot is allowed to deform when obstacles are hit. This paper describes the sensor systems developed for collision detection on this robot. This includes an analogue bumper, a geometry-measuring system and an IR proximity detector of users helping themselves to drinks.

1 Background and concept

ButlerBot was born from the wish of the School of Computing, Communications and Electronics of the University of Plymouth to have an attractive robot demonstration to show in local schools and open days. The function of the robot is to to serve drinks and snacks to members of the public. Hence, the specifications included light-weight, 5-10Kg, and ease of disassembly to facilitate transport in the trunk of a car.

This was also an opportunity to experiment with some new concepts. We opted for a narrow design, around 30 cm in diameter, to facilitate displacement in a crowd. This was expected to pose interesting balancing control problems. The anticipated close proximity with people made us re-think about collision detection. Instead of providing the robot with a multitude of sensors (e.g. Pan and Zhu, 2005), it was decided to use the body of the robot itself as a contact sensor. This led to the concept of "compliant geometry" described in section 2. Other sensors include an analogue directional bumper (section 3) and an array of IR sensors that is used to detect a user's hand that is taking a drink on the tray (section 4). The paper ends with a summary of future and ongoing work (section (5).

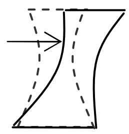

A) B)

Figure 1. (A) CAD representation of ButlerBot. (B) Current state of the prototype. The tray has a height of 95cm.

Waiter robots are popular as a demonstration platform. Firstly, because they take on a real-world challenge — as opposed to service robots in tightly controlled environments (e.g. Acosta *et al.*, 2006). Secondly, because they have a high entertainment value, giving the development of the hardware and software a certain purpose which appeals to students. There have been several demonstrations of robots serving snacks, and sometimes drinks, at various receptions. Most built on a standard robot platform, such as a Nomad Scout (Maxwell *et al.*, 1999) or the B21r platform (Clodic *et al.*, 2006), and rely on off-the–shelf sensors, such as sonar, IR and colour vision, to navigate through the crowd. ButlerBot on the other hand uses a custom built chassis, making to robot cheap and light weight, and integrated sensors, tailored to sensing egomotion while at the same time being an integral part of the robot's body.

2 Compliant geometry

2.1 Compliant Geometry Mechanics



The compliant geometry of the robot allows the body to deform. The side of the body is to be covered with textile. An impact at any point on its textile cover will deform the textile slightly but also tilt the top of the body away from the impact. A compliant body has many safety advantages in populated environments, such as a party or conference reception.

Many robots use a mobile outer shell to detect collisions, e.g. in the Rug Warrior (Jones and Flynn, 1993). In ButlerBot however, the body itself is the detector. While compliance has been investigated for couplings and joints (see e.g. Trease et al., 2005; Meyer et al., 2004), we are not aware of other work using the whole body as a compliant system.

Inside the robot is a light-weight support structure. The tray of ButlerBot is supported by 4 poles which have foam dampers at the end. Additionally 4 strings stretch from the centre of the tray down to the edge of the base like the stays of a boat mast, see figures 1b and 2. Each string incorporates a spring to allow flexibility. The 4 poles are mounted off-centre, which allows the tray effectively to shake in the horizontal X-Y plane.

The springs have a sensor attached (potentiometer Pot in figure 2) in order to measure their extension. This allows estimating the position of the tray at the top and the amplitude and direction of the shaking. There is a sensor in the spring aligned with the X-axis and another sensor in the spring aligned with the Y-axis.

2.2 Side impact detection

When the robot accelerates forward, the compliant structure is excited into oscillation making the robot lean forward and backwards. The directions of the oscillation are in the same plane as the robot's acceleration (Figure 3).

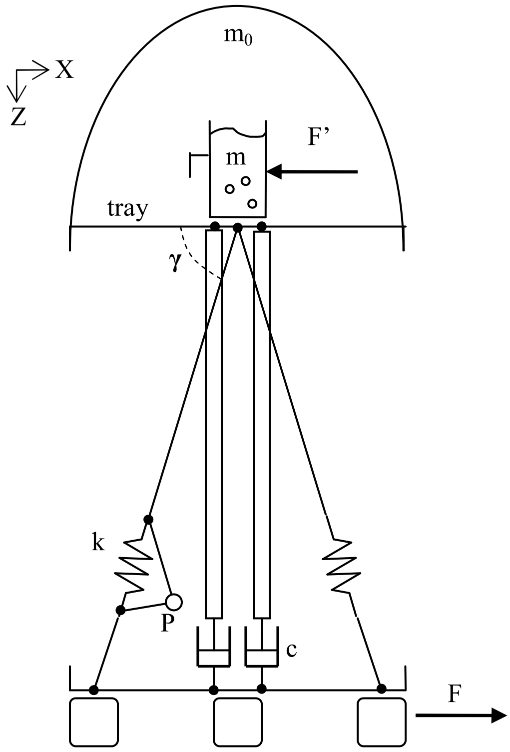


Figure 2: Side view (X-Z plane) of ButlerBots compliant body. Springs (k), off-centre poles with dampers (c), Acceleration force F causing the reaction F' on load mass m and tray mass m_0.

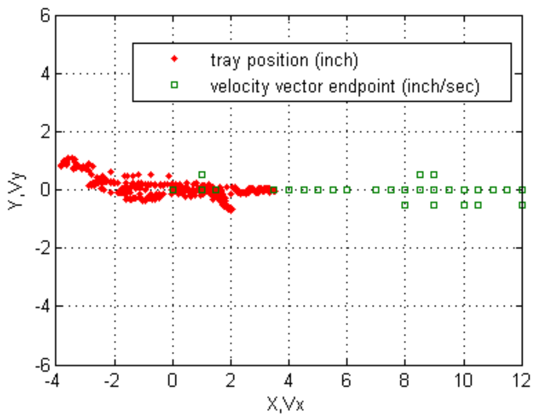


Figure 3: An acceleration of the robot along the x-axis caused oscillation of the drinks tray in the X-Y plane ("tray position"). The robot's base is located at (0,0) with a velocity vector along the x-axis. Note that the shaking is aligned with the robot's direction of movement.

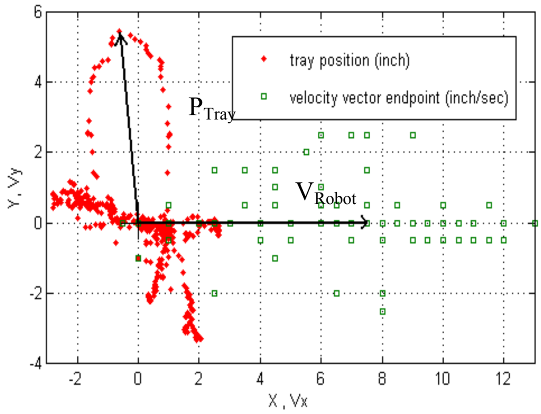


Figure 4: Direction of movement and shaking of the drinks tray in the X-Y plane. V_{Robot} is the velocity vector of the robot driving forward. In this case the robot is hit by a bypassing human, causing the tray to lean into the positive Y direction (P_{Tray}). The scatter in the robot's velocity vector shows that the robot had to correct its course after the impact.

A misalignment between the robot's velocity (or acceleration) vector and the tray position is used to indicate a collision. A significant disturbance of the tray can be easily recognised by the robot if the direction of movement is approximately perpendicular to the direction of the impact disturbance. However, if the impact is in the direction of movement, the recognition of the impact is more difficult, since the robot is shaking in this direction anyway. For this case a dynamic model of the tray is required.

2.3 Dynamic Model of the compliant structure

Using several assumptions for simplification, the dynamic model of the tray can be reduced to a two dimensional mass-spring-damper system in the X-Y plane (Rao, 2004). The angle **γ** in figure 2 can be assumed constant, since the movement of the tray is small compared to the height of the robot. As a consequence the spring exerts a tangential force F' on the tray:

$$F^{'} = F_{sp}\cos(\gamma) \quad \text{with} \quad \cos(\gamma) = \text{constant} \qquad (1)$$

where F_{sp} is the linear force exerted by the spring. The same assumption can be made with the dampers, effectively creating a mass-spring-damper system along the X axis and another one along the Y axis. We also assumed for simplification that the two systems have no cross coupling effect, which reduces the system from a MIMO system to two SISO systems in X and Y axes with the force F as input and the displacement of the mass $m + m_0$ as output.

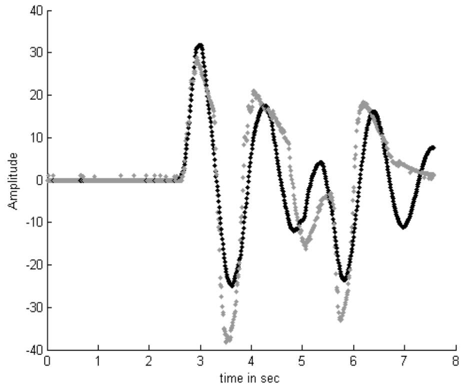


Figure 5: x-position of the tray in grey, model in black. The robot accelerates from rest at approx t=2.5 sec. Course corrections and deceleration are cause of an increase in amplitude at t=6 sec. In this case the total mass of the tray was 2.5 kg and the model had a natural frequency of $\omega_n = 5.4\, rads \cdot \sec^{-1}$.

The mass-spring-damper model, a second order differential equation, has been implemented into the embedded processor [2] as a difference-equation. Therefore the robot has a good idea of the position of the tray in real time. The input to the model is the acceleration force vector which is derived from the optical shaft encoders on the omni-directional wheels. The actual position of the tray is taken from the sensors on the springs. The position of the model is now compared to the actual position, giving rise to an error e(t) (Figure 5).

2.4 Estimating the load carried

Depending on the number of drinks on the robot the mass of the mass-spring-damper system will change. In order to find the correct model and hence find the mass of the drinks the processor constantly compares a range of models with the measured data for the first second of movement. After one second it will lock onto the model with the least error (Figure 6). This assumes that people will not attempt to change the load (e.g. glasses) of the robot while it is moving. The robot will reconsider its model every time it accelerates from rest. The tray handling detector in section 4 allows stopping the robot when the load is changed.

[2] Colibri board using Intel XScale® processor PXA270 520MHz.

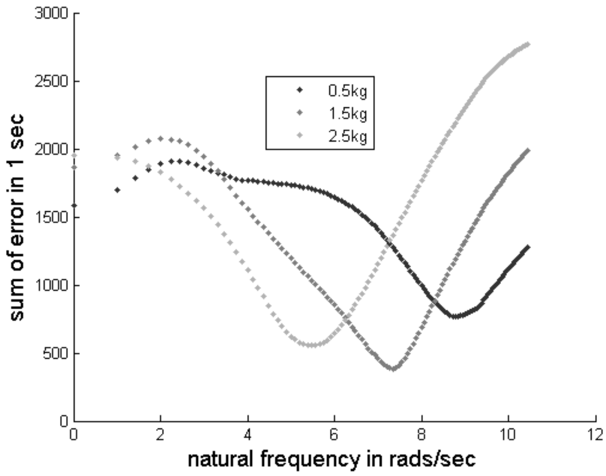


Figure 6: A series of models with natural frequencies from 0 to 11 (along the x-axis of the graph) are compared to the actual response. The error accumulated between the model and actual response within the first second is shown in the Y axis. The robot will chose the model with the minimum error. The graph clearly shows the error minima for a variety of tested loads (0.5 kg, 1.5 kg , 2.5 kg) .

The weight of the drinks on the robot can be derived from the natural frequency ω_n the no-load weight m_0 and the spring stiffness k.

$$m = \frac{k}{\omega_n^{\ 2}} - m_0 \qquad (2)$$

Alternatively a weight sensor could be used to determine the mass, although this information can be obtained here for free.

2.5 Front Impact detection

An error between the model and the actual movement of the tray indicates an impact , figure 7. To be sure a collision has occurred the robot must observe the error over a period of time. If over this period the error always stays large, a collision has occurred. This ensures that the collision detection is not triggered by small errors (noise) between actual measurements and the model. The decay of the curve after the impact is cause by a moving average that tries to adjust the neutral centre position of the tray. The neutral centre can change if a heavy load is put on the robot, forcing it to tilt to an arbitrary side at rest. The oscillations of the liquids were negligible.

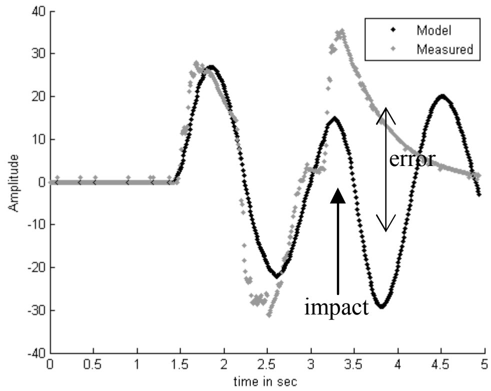


Figure 7: Collision with an obstacle in front of the robot caused the error between model (black) and actual tray position (grey) to increase.

3 Analogue bumper

The compliant geometry will detect collisions at any point of the robot's body, except the base. For that reason, the base is provided with a bumper system. This is made of a floating disk attached with springs. An impact on the bumper disk will cause the robot to stop and avoid the area. The direction of impact can be retrieved from the bumper using three patches with a greyscale gradient (Figure 8) that are read by an IR reflective sensor. The response of the sensor is almost linear over the range of greys used here, Figure 9. These IR sensors are attached to the robot's base. The patches are attached to the floating disk with the directions of their gradients making angles of 120 degrees. For mechanical reasons, the patches themselves are not at 120 degrees to each other , Figure 8.

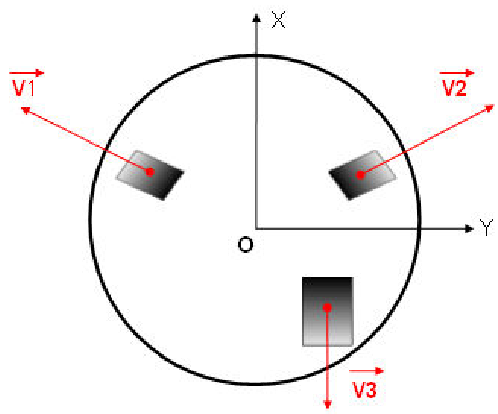


Figure 8. Position of the grey-scale gradient patches with gradient direction indicated.

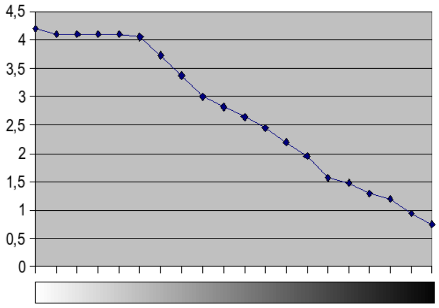


Figure 9. IR sensor's response (in Volts) using a linear grayscale patch (5 mm distance of the sensor from the sheet).

The IR sensors are approximately centred on the linear party of the grey-scale gradient. Such a system can easily be calibrated when the robot is powered on. Whatever readings the IR sensors give at that time define the $X = 0$ and $Y = 0$ position of the disk.

The XY position of the bumper disk is calculated as follows. In the formulas below, δ_1, δ_2 and δ_3 are the distance variations respectively proportional to the tension variation on the sensor 1, 2 and 3.

$$X = \frac{1}{3}[(\delta_1 + \delta_2)\sin(\pi/6) + \delta_3] \qquad (3)$$

$$Y = \frac{1}{2}(\delta_2 - \delta_1)\cos(\pi/6) \qquad (4)$$

These calculations assume that the distance between the sensors and the disk is stable. This requires some care in the mechanical design.

4 Tray handling detector

The robot needs to detect whether a user takes a glass or replaces one, so that it can stand still during the load change. The approach explored here for handling detection is a semi-circular array of IR emitters and receivers facing upwards (figure 10). The array is attached at the front of the tray and should detect a hand entering the space above the tray.

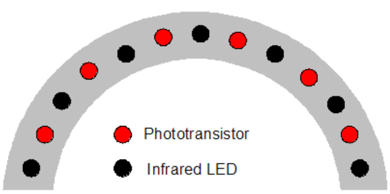


Figure 10. Array of IR emitters and receivers facing upwards

To improve the sensing distance, we have used modulated emitters and tuned receivers, Figure 11.

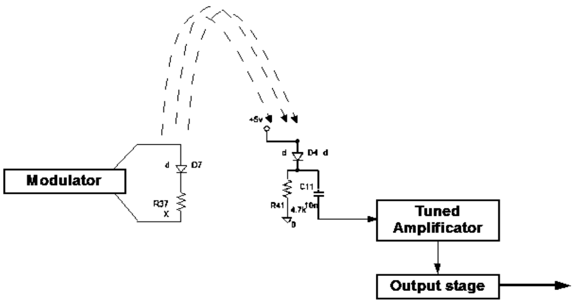


Figure 11. Detection circuit principle, showing a modulated emitter and tuned receiver.

Figure 12 shows the output voltage from the receiver for a hand placed at various distance from the sensor. It shows that obstacles can be detected up to approximately 25-30 cm. Whether this is appropriate for the planned use will be established during future tests.

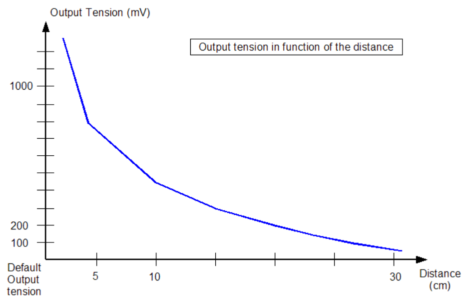


Figure 12. Response of the tray handling detector array as a function of the distance of a hand from the detector.

Several problems were encountered during the design of this sensor system. Because the beam reflected by a hand or a dark fabric can be very weak, it is necessary to use high-power LEDs which creates parasitic signals in the receiver circuit transmitted through the power supply line. Another problem is the variable sensitivity of the photoreceiver. The sensitivity generally decreases with the ambient light due to the internal transistor properties. We are currently working on an upgrade of the circuit design to eliminate this problem[3].

[3] We will also consider an approached based on IR transmission (beam cutting) rather than the current reflective system, as kindly suggested by one of the reviewers of this paper.

5 Summary and future work

A prototype service robot has been successfully built and field tested with loads up to 2.5kg. The design of this ButlerBot poses interesting sensing problems, some of which have been discussed here. Ongoing work also focuses on the design of the behaviour of the robot. We hope to make ButlerBot operate effectively as a butler in a crowded environment. This will include a return-to-base function when its tray is empty. Stage 2 development also includes a stereo vision sensor to detect and localize user's faces and advanced dynamic stability control.

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