The Anthropomimetic Principle

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Abstract

Most humanoid robots are essentially conventional robots that fit within the morphological envelope of a human. However, for robots that are intended to help in the understanding of human cognition and action, a much higher level of biological inspiration may be necessary. This paper sets out some of the requirements for an anthropomimetic robot – one which imitates not just the human form, but also the biological structures and functions that enable and constrain perception and action – and describes the design, construction, and initial performance of such a robot. The findings to date indicate that the combination of a realistic skeleton, series-elastic actuators, and a foveated vision system gives a unique insight into the problems the human brain has to solve in the areas of perception and action.

1 Introduction

At present, there are approximately 70 major humanoid robot projects being undertaken around the world [1]. It might be expected that such a high level of activity would generate a constant stream of new findings relevant to the field of biologically inspired robotics, but unfortunately this does not seem to be the case. Perhaps the main reason for this is that the aim of the typical humanoid development programme is simply to engineer a mobile robot that fits within a broadly human envelope, and employs a broadly human range of movements; there is no intrinsic requirement to draw inspiration from the ways in which humans actually produce and control their actions.

This is not intended as a criticism of these projects, because there are many different reasons for adopting a predominantly morphological perspective. For example, NASA [2] is interested in robots that can undertake maintenance and repair tasks on spacecraft designed to be worked on by humans, and so a human morphology is the logical choice. Many Japanese humanoid robots, such as Honda's Asimo [3], are intended to assist humans in normal domestic or work tasks, and a human-like morphology facilitates human-robot interaction and cooperation, as well as being matched to the human-centred environment. Some entertainment robots, such as the Sony QRio [4], are designed to charm by imitating humans. All of these robots are actuated and controlled using conventional engineering techniques of an extremely high standard, and all meet the specified requirements, but none of them draw on any further biological inspiration.

Of course, there are humanoid programmes that do go beyond mere morphological similarity. ATR's DB (Dynamic Brain) project [5] uses a hydraulically powered humanoid as a test-bed for movement control algorithms inspired by the neural structures and processes thought to be used by the brain [6, 7]. A more recent theme has been the development of several walking robots that use explicitly biologically inspired techniques to produce extremely efficient and natural-looking bipedal locomotion [8]. Such robots apply the ideas of passive dynamic control – the exploitation of resonances, oscillations, foot shape, and passive compliance. These and other examples, taken together, point us in a direction that may enable both the design of better robots, and an increased understanding of human movement control: *why not build a humanoid robot that faithfully copies the essential physical structure of a human, and attempt to control it using the same methods as the brain does?*

We propose to call such machines *anthropomimetic* robots. We believe that this shift of emphasis from the outward form to the nature of the internal mechanisms carries the promise of transforming not only humanoid robotics, but also the way in which robotics is perceived by the lay community. However good the cosmetic appearance and however soft the flesh-toned latex of the latest Japanese robotic receptionist, people are always aware of the artifice, knowing that the apparent humanity is only skin deep. But if the robot's internal form and function is also close to our own, the question of the boundary between the natural and the artificial will become more acute, and the debate about the nature of the relationship between robots and ourselves may take on a new urgency.

This paper describes the progress of an attempt to build a truly anthropomimetic robot. The next section sets out the background to the project; section 3 describes the technologies used in building the robot; sections 4 and 5 describe the construction and behaviour of the first two prototypes, and section 6 discusses the main findings so far.

2 Approaching anthropomimesis

The robot described in this paper is a spin-off from a larger project aimed at building a robot with at least the potential for some form of consciousness. Several writers on the subject (e.g. [9], [10]) have identified the existence of an integrated internal model of the self as being a key component of consciousness. Such models are thought to include many aspects of the body, including how it is controlled. The central idea behind the parent project was to build a robot that could develop such a self-model, and this led to the question: what sort of body would the robot need to form the kind of internal model that might support consciousness? For want of any better information, the obvious answer is: a body similar to that of a human, since human consciousness is the only consciousness about which we have any reliable information. However, when we reviewed the state of the art in humanoid robotics, it rapidly became clear that almost all existing humanoids had bodies that were only superficially similar to humans, and that they were moved and controlled in ways very different from those of humans. It was necessary for us to start from scratch.

3 Materials and components

The technical problems we faced in the construction of the robot centred around two key problems: the skeleton; and the musculature. Of course, these could not be treated independently, because each imposed constraints on the other. In the event, however, the first strategy we tried worked very well: it was simply to copy the skeleton as best we could – at life size – using purely passive elastic elements to represent the musculature, and then to investigate possible ways of constructing and installing suitable powered muscle analogues.

3.1 The Skeleton

The adult human skeleton is at first sight extremely complex, containing 206 bones. (Interestingly, we have 275 bones at birth, but many have fused by maturity.) However, since more than half are in the hands and feet, and since our bilateral symmetry means that most bones have a mirror image bone with identical structure and function, the problem of building a working skeleton may just be very difficult rather than completely intractable.

Our first problem followed directly on our decision to model the bones of the skeleton: how could we model bone-like structures? In a conventionally engineered robot, the actuators are built into the joints, and the only constraints on the links between the joints are those of rigidity, clearance, and weight. However, as is clear from any anatomy textbook [11, 12], or more spectacularly from the plastination preparations of Gunther von Hagens [13], bones must also provide the points of attachment for the tendons, and this can be critical in determining how the mechanical advantage of a muscle-tendon-joint system changes as the joint moves. (Indeed, in many cases the bone will form also surface over which the tendon moves.) In addition, the joints are not limited to simple hinges or universal joints, but may accommodate rolling or sliding movements. To machine, fabricate, or cast a large number of different such components by conventional methods would be difficult and expensive.

The solution was to use a new type of engineering thermoplastic known in the UK as Polymorph, and in the US as Friendly Plastic [14]. Technically a caprolactone polymer, it is polythene-like in many ways, but when heated to only 60 degrees C (for example, by plunging into hot water) it fuses (or softens, if already fused) and can be freely hand moulded for quite some time, finally resetting at around 30 degrees. It has a distinctly bone-like appearance when cold. Since it is a true thermoplastic, it can be reheated and remoulded as many times as is necessary; it is possible to soften it locally, which makes it particularly easy to use. It is readily moulded around other components and materials – for example, it can be used to form a ball and socket joint by moulding it around a metal sphere mounted on a rod. Its slight contraction on cooling can be used to ensure tight joints when it is moulded around other components.

In practical engineering terms, it is tough and springy. Its tensile strength is good – Polymorph has the highest tensile strength of all the capralactones, at 580 kg/cm^2. It can be further strengthened (and stiffened, if necessary) by adding other materials, such as wire, or metal rods or bars.

3.2 Muscles and actuators

Although there are many different types of muscle in biology, the 650 or so human skeletal muscles are fairly stereotyped. A muscle consists of a number of muscle fibres (or cells) arranged in parallel, and connected at each end to a common tendon, the elastic connection to the skeleton. When a muscle fibre is stimulated by its associated motoneuron, it fires and contracts momentarily, exerting force on the tendon. A given motoneuron innervates only a single muscle, but controls a number of muscle fibres within that muscle, typically between ten and a hundred; the combination is known as a motor unit. A given muscle is innervated by a number of motoneurons, in many cases by hundreds of them. A sustained muscular contraction is achieved by repeatedly stimulating individual motor units, and the strength of the contraction is modulated by varying the number of motor units activated. Muscle is elastic tissue, and the force exerted is a function not only of the motor unit activation but also of the length of the muscle, which of course changes if the associated joints change position as a result of the balance between the load and the effort.

In many animals there are reflex and auxiliary subsystems in place to enable more sophisticated closed loop control of muscular systems. The level of complexity varies, but mammals are at the top of the tree, with sensor systems for measuring muscle tension (via the Golgi tendon organ), and the effective length of a muscle (via the muscle spindle). These are involved in various feedback systems, and the sensitivity or gain of some of these (e.g. the stretch reflex) can be centrally controlled.

The essential nature of many skeletal muscle systems derives from two factors: muscles (and tendons) are elastic, and so can only pull and not push; and most degrees of freedom are controlled by antagonistic arrangements of muscles, where the effect of one muscle is opposed by that of one (or more) others. This has two consequences. First, if a muscle and its antagonist are stimulated together, the affected joint will move, changing the lengths of the muscles, until their effects balance the imposed load. This position is known as the set point. Second, the resistance offered to an externally imposed disturbance at the set point – the impedance – is primarily a function of the tension and elastic properties of the muscles involved. Both of these factors make skeletal muscle systems very different from conventional robotic actuation arrangements; as will be seen, these differences have far-reaching effects.

The typical robotic actuator is very different from muscle. In most applications, precise control of trajectory and/or position is of paramount importance, and robotic actuators tend to be extremely stiff to enable this precision. This has two main consequences. First, any unplanned impact with environmental obstacles can impose a shock loading on the transmission (typically a gear train) that may lead to failure or degradation. Second, an unplanned impact with a human can represent a serious safety hazard. The standard ways of dealing with these problems (strengthened transmissions, safety cages) are unsuitable for mobile humanoid robots. As it happens, one technology for dealing with these problems can be adapted to mimic many of the desirable properties of muscle.

3.2.1 Series-elastic actuators

The solution of interest is to use a conventional high impedance actuator, but to place it in series with a source of compliance. At its simplest, this can merely be a rubber buffer to protect gear teeth from the peak shock. However, in many applications, there is also a requirement for good force control, and this offers a further challenge. An excellent compromise is offered by the series elastic actuators first developed at MIT [15], and later commercialised [16]. In these, the source of compliance is a spring; by simply measuring the extension or compression of the spring, the force can be accurately known, and any deviation from the required force can be compensated by using a high gain position controller for the conventional high impedance actuator. Unfortunately, it seems to be impracticable to use these high-specification actuators on a life-size humanoid, for reasons of expense, size, power, and weight.

What other options are available? One possible approach would be to use commercial pneumatic actuators. These can be relatively small and light, although their characteristics are in many ways undesirable, as instead of exploiting their intrinsic compliance, they are usually engineered to reduce it to obtain reasonable position control. An art project [17] has investigated the use of such actuators for an anthropomimetic device in a very different context, but with some success. Like us, they aimed to build a life-size humanoid with a fully articulated skeleton, but their concern was driven solely by artistic considerations, in that they wanted to reproduce human movement patterns rather than to produce an effective mobile robot. Using movement scripts derived from humans, they demonstrated what appear to be very fluid and smoothly coordinated movements, but did not undertake any functional analysis of the source of the observed characteristics.

Our eventual decision was to investigate the use of the series elastic technique, but to use a much lower level of engineering sophistication. Our approach was driven by considerations of cost, size, weight, performance, and power. The cost and size had to be as small as possible - the torso alone would require at least forty powered degrees of freedom. Maximum performance was critical - some of the actuators would be required to generate forces of the order of 1000N. In order to avoid problems with the distribution of power, an actuator with a built-in power source was highly desirable.

Our solution took advantage of the mass production of a common domestic device – the electric screwdriver. These are designed to produce torques of around 3Nm in from NiCad battery packs of 6V nominal voltage, and the direction of rotation is electrically switchable; backdriving against the set direction is prevented by a sprag clutch. The elastic element is provided by marine grade shock cord – a sleeved natural rubber core available in a number of thicknesses. For light loadings we use a 5mm type, and for heavier duty a 10mm version. The shock cord is terminated at each end by 3mm thick braided Dyneema kiteline with a working breaking strain of 250kg. This material, also known as Spectra, is a heavy molecular weight polyethylene (HMWPE), 40% stronger than Kevlar, and with negligible stretch. By winding the kiteline round a 10mm spindle driven by a standard good quality screwdriver motor and gearbox, we can achieve tensions in excess of 520N; by overdriving a rather better motor, we can increase this to around 860N. The maximum current draw is of the order of 20A, giving reasonable endurance from the custom 7Ah battery packs.

Many of the techniques developed can be seen in Figure 1, an early investigation of an unpowered knee joint. The upper half of the joint contains two large chrome balls embedded in Polymorph – one is clearly visible on the left. When the knee is straightened, the two balls rest in the moulded cups in the lower part of the joint, partly locking the joint to give some stability. As the joint rotates during flexion, the load is partially transferred to the moulded ball housing, and the joint becomes a rolling joint. The kneecap, or patella, is continuous with the lower part of the joint, but is thin enough to bend under the load of the tendon from the extensor motor. The termination of the flexor tendon can be seen on the left. The joint is held together by the tension transmitted through the tendon connecting the lower leg to the upper joint housing, and passing through a hardened insert moulded into the lower leg. It is clear that there are enormous differences between this type of joint and the conventional geared hinge joint forming most robot knees, and it is overwhelmingly likely that the functional characteristics of the joints will also be different. It may well be that the anthropomimetic knee is inferior to the engineered knee in many respects, but the point is that the anthropomimetic knee is a better representation of the control problem that the brain has to solve.

Figure 1: An early knee design using Polymorph

4 The first prototypes

Before construction began on the final prototype, we carried out a number of design studies and partial prototypes. Figure 2 shows the first prototype of the head and neck. It is clear that the neck is made up of several vertebrae – four in all – but they are much longer than their human equivalents. There are two reasons for this. First, it would be impossible to accommodate all the motors and tendons in a strictly faithful copy, and so reducing the number of vertebrae at least maintains some degree of qualitative fidelity. Second, it is not yet possible to build a hand able to expose held objects to different points of view by manipulating them, and a possible remedy for this is to provide the head with rather more than the usual range of movement to enable a more through visual inspection. This was done by increasing the length of the vertebra to enable the head and neck to crane and rotate in an exaggerated manner. In this version, the neck has two motors fitted – they are clearly visible just below the single eyeball. Each motor and gearbox is moulded into a Polymorph housing which provides the fixing points, and also supports the spindle onto which the kiteline is wound.

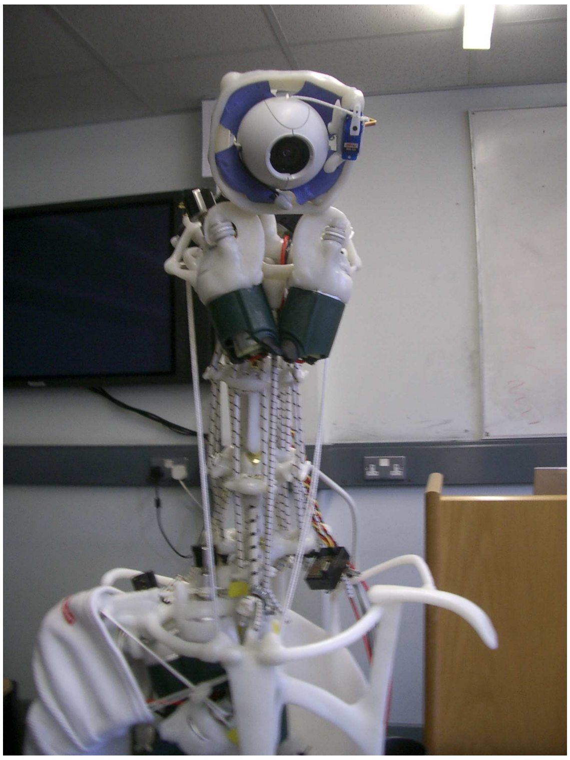

Figure 2: The prototype head and neck.

Figure 3 shows the first prototype of the torso and arm. The structure of the spine, which was purely passive at this stage, shows six vertebrae with rather exaggerated lateral extensions. Each vertebral joint was formed around a chromed sphere cast into one vertebra, and free to rotate within a matching cup in the other vertebra. The shoulder joint was quite a faithful rendering of the real thing – in fact, it could be dislocated in exactly the same way as a human shoulder – but did not include the shoulder blade. (The function of the shoulder blade is quite complex – see [ ] for what we believe is the only example of a robot with a correctly functioning but rather abstract shoulder blade).

These initial subsystem prototypes were extremely useful in developing the appropriate modelling technology. However, the first indication of

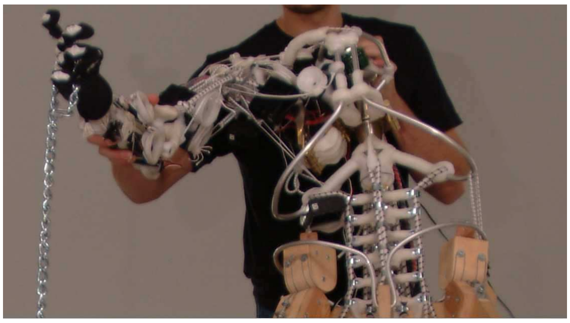

Figure 3: The prototype torso and arm

the nature of an anthropomimetic robot came from the first system prototype, CRONOS, which com bined a torso, arm, and head. As can be seen from Figure 4, the sheer profusion of powered and unpowered tendons gives a strong qualitative impression of a biological system. This impression soon gives way to the realisation that the robot represents something qualitatively distinct from a conventional robot, even before it is powered up. You take his hand and shake it: it moves easily, *and so does his whole skeleton*. This multi-degree-of-freedom structure, supported by the tensions between dozens of elastic elements, responds as a whole, transmitting force and movement well beyond the point of contact. You take his arm and push it downward: the elbow flexes, the complex shoulder moves, and the spine bends and twists.

Figure 4: The first operational prototype, CRONOS.

When the robot is powered up, it moves to some equilibrium posture, but the character of the movement is again highly distinctive, because the disturbances due to the robot's own movement are propagated through the structure just like the externally imposed loads. Of course, if all that is wanted is a robot that fits into a human envelope, is able to operate in limited ways on a largely static and predictable world, and is tractable from the point of view of control, this flexibility is nothing but a nuisance. But if the target is a robot that as far as possible works in the same way as a human – an anthropomimetic robot – then we must face up to the problems that robots like CRONOS present.

These problems are not simply to do with the difficulty of controlling such a redundant and flexible structure. The intention is that, like a human, the robot will be predominantly visual, and so it has been equipped with a visual system that is also anthropomimetic (Figure 5). However, it differs from humans in having a single central eye; this simplifies visual processing enormously, and can be justified by the fact that around 20% of humans do not perform stereo fusion, yet their performance on visual tasks is within the normal range. The imaging unit (currently a 640 x 480 colour webcam with a 25 degree field of view, shortly to be replaced by a specialist high resolution camera with a 90 degree field of view) is mounted in a model eyeball, and is moved by functional analogues of the six extraocular muscles, able to control rotation as well as pan and tilt.

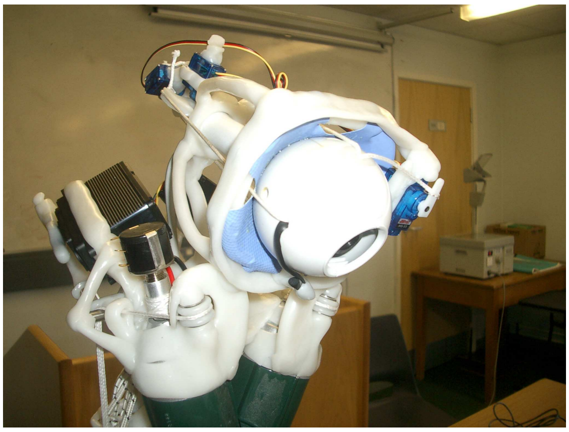

Figure 5: The prototype vision system

In order to reflect the nature of the human visual system, the first stage of image processing involves the application of a transform to mimic the reduction in density of photoreceptors between the fovea and the periphery. A foveal system places a heavy emphasis on the accurate and precise control of gaze direction, and the disadvantage of an anthropomimetic robot is immediately apparent: it provides a much less stable platform for the visual system than does a conventional robot. In the absence of any dedicated means of stabilisation, even the slightest change in external or inertial load is reflected through the whole skeleton, usually causing considerable movement and vibration at the extremity of the body, where of course the visual system is mounted. In a conventional robot, with a conventional unfoveated vision system, these problems would not arise; however, their presence in the anthropomimetic robot emphasises that they must have been solved by the brain, and so we will be pushed to solve them, perhaps even in the same way. (We have ordered an inertial measurement unit to act as a source of input analogous to that from the vestibular system.)

5 The second prototype

Building on the knowledge gained from the early prototypes, a second prototype has now been constructed and is undergoing further development and testing. It is still limited to a torso, head, and arms (the second arm has not yet been attached in the figure). The original arm design has been modified. The first shoulder design seemed unnecessarily complicated, and so several engineering simplifications were made. The new arm is superior in almost all respects, but its range of movement is now rather limited in the vertical direction, and it is in the course of being redesigned to include some features of the original. The hand has also been redesigned, mainly because the prototype hand occasionally broke under load. In the original hand, each finger was formed by compressing softened Polymorph with an edge at suitable intervals to define each joint and to form a hinge. These hinges could not always withstand the forces imposed on them, and so in the new hand, two lengths of kiteline are moulded into the finger before the joints are formed, ensuring that each hinge is reinforced with two strands of Dyneema. There have been no failures since. Once again, this illustrates the suitability of Polymorph for this type of construction.

Figure 6: The head and torso with one arm fitted

Table 1 lists the powered degrees of freedom currently available, and relates them to the skeletal musculature where appropriate. Note that some degrees of freedom, such as those dealing with eye

No.	Section	Description	DOF	Actuator	Muscular equivalent
1	Eye	Eyeball orientation	Pan	Servo	Lateral/medial rectus
2	"	"	Tilt	Servo	Superior/inferior rectus
3	"	"	Rotation	Servo	Superior/inferior oblique (partial)
4	Head and neck	Head pitch and rotation	Head pitch and left rotation	Servo	Simplification of many muscles
5	"	"	Head pitch and right rotation	Servo	Simplification of many muscles
6	"	Neck can crane forwards and sideways with passive return to upright	Neck forwards, head rotate left	Motor	Sternocleidomastoideus
7	"	"	Neck forwards, head rotate right	Motor	Sternocleidomastoideus
8	"	"	Neck left	Motor	Simplification of many muscles
9	"	"	Neck right	Motor	"
10	Shoulder	Arm can raise and rotate	Arm raise sideways	Motor	Lateral Deltoid
11	"	"	Arm raise forwards	Motor	Anterior Deltoid
12	"	"	Arm adduction and internal rotation	Motor	Pectoralis Major
13	"	"	External rotation	Motor	Infraspinatus
14	"	"	Raise arm and external rotation	Motor	Teres Minor
15	"	"	Retract arm and internal rotation	Motor	Teres Major
16	"	"	Flex arm and raise forward	Motor	Biceps Brachii
17	Elbow	Controlled by (16), (17) and (18)	Extend arm	Motor	Triceps
18	"	"	Flex arm	Motor	Brachialis
19	Wrist	Pitch and yaw	Inwards and upwards	Motor	Simplification of many muscles
20	"	"	Outwards and upwards	Motor	"
21	"	Pitch	Downwards	Motor	"
22	"	Roll	Rotation only	Motor	"
23	Hand	Grip with passive release	Grip	Motor	"
24	Waist	Support from spine limits motion in all directions	Back and left	Motor	"
25	"	"	Back and right	Motor	Simplification of many muscles
26	"	"	Forwards	Motor	Mainly equivalent to Rectus Abdominis
27	"	"	Rotate left	Motor	Simplification of many muscles
28	"	"	Rotate right	Motor	Simplification of many muscles

Table 1: Powered degrees of freedom with one arm fitted.

movement, are implemented using conventional servos because the load is light and constant.

The behaviour of the second prototype has been studied in several contexts, and has proved very illuminating. Simply moving one degree of freedom, even jerkily, produces what looks like a fluid and coordinated whole-body movement which all observers to date have agreed is very natural and 'biological looking'. This is because the static and dynamic loads produced by the movement are transmitted through the skeleton and the elastic linkages, producing what we have called 'passive coordination'. Repeating the same movement under (open loop control) with a load (such as the round weight shown in Figure 6) produces an equally natural movement, but one in which the weight and inertial forces produce a rather different trajectory and finishing point. This emphasises that the command for such a movement, to be successful, must take account of the anticipated loadings; we believe this is unlikely to be successful if done purely reactively, and that feedforward compensation – anticipating and predictively cancelling the effects of the load – will be necessary for almost any movement, a somewhat daunting prospect when designing the controller.

6 Conclusions

Although we are still dealing with a prototype, we can already see that the anthropomimetic approach is distinct from the standard humanoid approach, and that it is much closer to the type of biological inspiration discussed in this symposium. The observations to date indicate that the combination of a realistic skeleton, series-elastic actuators, and a foveated vision system gives a unique insight into some of the problems the human brain has to solve in the areas of perception and action. We are no closer to solving any of these problems than we were at the start of the project, but at least we have some confidence that we are moving in the right direction.

Acknowledgements

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