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The Initial Design and Manufacturing Process of a Low Cost Hand for the Robot iCub

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***Abstract*— This paper describes the design of a new hand for the robot iCub. Developed as part of the European project RobotCub the iCub is a robot baby based on an 18 month to 2.5 year old child. The current iCub hands are under-actuated which means they are not as dexterous as a true child's hand. The hand designed in this work has a total of 22 degrees of freedom of which 18 are independently drivable. In order to minimise weight and cost the hand has been produced from Acrylonitrile Butadiene Styrene (ABS) using 3D printing techniques. This removes the need for extensive machining which would add significantly to the overall cost of the hand. A prototype finger has been produced and tested and a full mechanical design is presented.**

I. INTRODUCTION

Advancing the understanding of human cognition is currently an active area of research within the neuroscience field. At the same time the robotics community is looking towards the use of artificial cognition for use in robot systems. The EU funded RobotCub [1],[2] project is a collaborative project between both neuroscientists and engineers with the aim of further developing and understanding cognitive processes.

The RobotCub project is based on the belief that manipulation of objects and interaction with the world around us plays a fundamental role in the development of human cognitive capabilities [2]. Many of the basic skills used by humans, such as locomotion and object manipulation, are learnt very early on in their development. For this reason the RobotCub project seeks to explore the development of cognition through the creation of a child like humanoid robot.

This robot, the iCub, aims to replicate both the physical and cognitive abilities of an 18 month to 2.5 year old child. Once completed versions of the iCub were distributed to researchers to develop the cognitive aspects of the project. This is being achieved by placing the robots in environments and scenarios where they will learn through interaction with the environment and objects and people within it.

To ensure that this interaction is as true as possible the robot must be a highly accurate representation of the infant inspiration. As a result the 'baby' robot, Figure 1, stands 100cm tall, fits within the general size and shape of a child, weighs less than 23 kg and has 53 of d.o.f. Whilst this number of dof is high, this is less freedoms than possessed by a child with particularly acute differences being in the spine, hands and feet which are simplified to ease mechanical design.

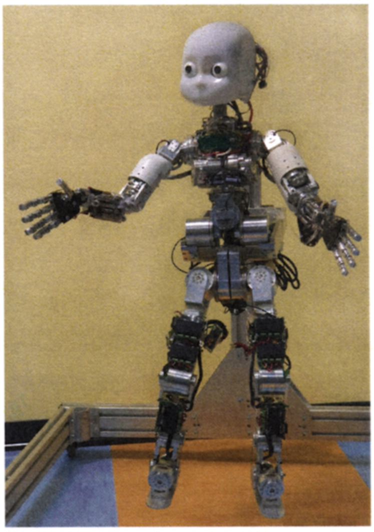

Figure 1 – The iCub robot

Differing reasons exist for the lower number of dof in each of these cases, however, focussing on the hands the major constraint is the physical size and performance required. In an attempt to maximise the dexterity of the iCub's hands whilst achieving a compact design they are under-actuated. Although each hand has just 9 controllable actions they in fact both have 20 joints with multiple joints being powered by a single motor [2][3]. By carefully selecting which joints are coupled, the dexterity of the hand can be maximised, whilst keeping the actuators required to a minimum. This is particularly important due to the limited space available resulting from the small scale of the robot. Despite this being perhaps the most compact dexterous hand developed for humanoids it is still only comparable in scale with the hand of an 8 year (not a 2 year) and is almost

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10cm from the base of the palm to the end of the middle finger as opposed to the 6cm seen in a 2 year old.

In addition, although capable of highly complex grasps and manipulations the fact that it is under-actuated means that it is not a true representation of a human hand. On an adult scale there are numerous examples of fully actuated anthropomorphic robotic hands. These include, but are not limited to, the Utah/MIT hand [4], Anthrobot Hand [5], Robonaut Hand [6], DLR-Hands [7], Remedi-Hand [8] and Ultralight hand [9].

The aim of this work is to develop a miniature fully actuated dexterous hand comparable in scale, mass and performance with a 2 year old human child for the next generation iCub.

The paper will begin by briefly examining the existing iCub hand. It then describes the production and assessment of a prototype finger before a full mechanical hand design is described.

II. EXISTING HAND SYSTEM

The current iCub hand has 20 degrees of motion and uses 9 Faulhaber motors to power it. Two motors are located inside the palm with the remainder positioned on the forearm with forces being transmitted to the joints using a cable drive. The hand also includes a 2 d.o.f. wrist capable of producing 0.65Nm of torque in both flex/extension and ab/adduction [2]. The motors and gearheads used to power the fingers have an output torque of 21.5mNm [3]-[11] although for under-actuated joints this power is shared between a number of joints.

The hand includes Hall Effect sensors for measuring joint positions as well has motor torque and cable tension sensors. These allow the hand to be used in both position control and force control modes.

III. DEGREES OF FREEDON

The main aim of this project was to increase the dexterity of the hand to more closely match a true two year old child's hand.

Figure 2 shows the degrees of motion to be included on the robot hand. There are a total of 22 degrees of motion in the hand of which 18 are independently actuated and four, the finger distal joints, are coupled to their respective medial joints. The thumb and fingers have 4 degrees of freedom with the exception being the middle finger which does not include lateral motion of the metacarpal. The decision to exclude this motion was taken to simplify the design and reduce the number of actuators, and was based on the fact that during spreading of the finger this joint typically remains static.

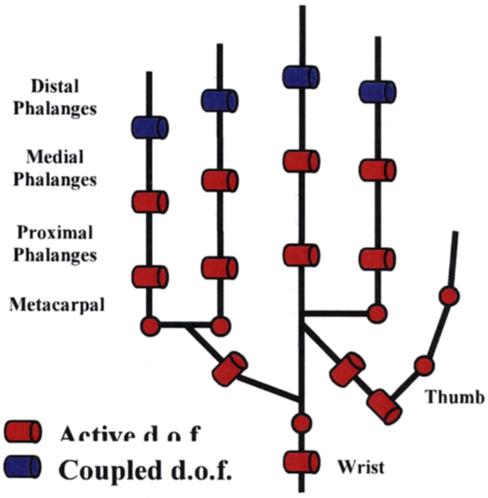

Figure 2 - Hand degrees of freedom

IV. ACTUATION

Whilst there are other actuators available which have been used successfully to power robot hands electric motors were selected in the project. This decision was based solely on the actuator and control hardware of the existing iCub system with which the hand would ultimately be integrated.

V. MATERIAL SLEECTION

The main material requirements for this project are that it be as lightweight as possible whilst possessing sufficient strength to enable small parts to be fabricated. Electric motors, which are the actuators used on the current iCub [2], have both lower power/weight and force/area performance than organic muscle. Therefore to allow the use of actuators that are sufficiently small to keep the robot within the target dimensions the mechanical structure needed to be as lightweight as possible.

Initially aluminium was chosen due to its relatively low weight, however, even this is 2.5 times the weight of the equivalent volume of flesh and bone. The weight could be reduced through the inclusion of internal cavities as with the existing iCub hand [2],[3] but whilst this is relatively easy to achieve in the palm it is more difficult in the fingers due to their small size.

Furthermore the coefficient of friction between pieces of aluminium is very poor (μ=1.05-1.35) meaning bearings would be needed to reduce wear and allow smooth motion of joints. This is the case with the current iCub hand [3] and the need to use bearings complicates the design and increases the cost, mass and dimensions.

For the above reasons it was decided to investigate constructing the hand from a structural plastic. The density of plastics is closer to that of flesh and bone. Also the frictional coefficients are typically much lower than that of aluminium. Chua et al. [16] describe a robotic hand constructed from polyethylene. The low material friction (μ=0.18-0.22) meant the joints could be produced without bearings, significantly simplifying the design. Tests for this hand without bearings suggested mean time between failures of 500-1000hrs which although low for an industrial robot is high for research prototypes.

	Nylon 66/6	**PTFE**	**PE**	**ABS**
Coefficient of friction	0.210-0.510	0.02-0.08	0.18-0.22	0.26-0.31
Density g/cc	1.07-1.70	0.70-2.30	1.16-1.30	0.89-1.09
Ultimate tensile strength (MPa)	30.0-269.0	10.0-45.0	46.2-60.0	31.0-49.0

Table 1 – Properties of selected plastics.

A comparative study was conducted for a range of plastics to determine the most appropriate. The key characteristics were weight, friction, strength and the ability to fabricate to small dimensions. Table 1 shows the material properties for four shortlisted materials. PTFE has the best friction performance but it has greater mass and less strength than the other materials. Polyethylene (PE) appear to offer the best all round performance and has been used successfully in similar projects [16].

The complexity and intricacy of the hand's design meant that the components would need to be produced using a computer controlled machine tool (CNC), injection moulding or similar technology. Both techniques are expensive. The cost of producing moulds is only justifiable if large numbers of products are produced and CNC time is expensive due to the high initial capital cost of the machines. 3D printing offers an alternative manufacturing technique for plastic parts but the materials used with such machines have tended to be highly brittle making them suited only to prototype production. However, modern production machines [ref] can use structural Acrylonitrile Butadiene Styrene (ABS) allowing final products, not just prototypes, to be produced. Whilst the material properties of ABS are not as well suited to the project's performance requirements as PE, it does still perform well in each of the categories. This is particularly so for product density which is comparable with the human body. In addition the major advantage of substantially reduced production costs when compared to CNC machining forms a high practical advantage. For these reasons it was decided to further investigate using 3D printing and ABS to fabricate the robot hand.

VI. PROTOTYPE FINGER

Initially to assess the suitability of the material and production method a single prototype finger was produced. The finger consisted of four links as seen in Figure 3. Each link includes two round pegs which extend from either side. These locate in holes in the proceeding link creating a moveable joint.

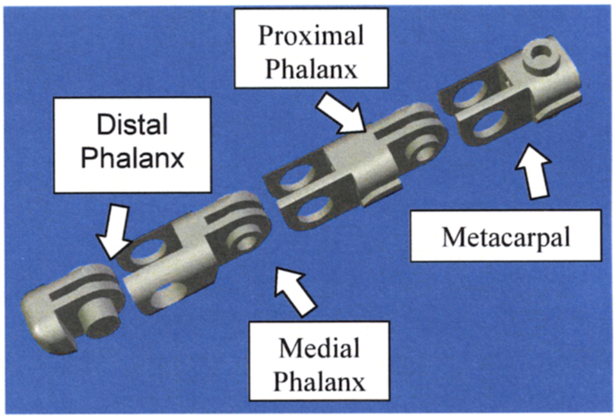

Figure 3 – Design of prototype finger

Each link was produced as a single part. If produced using traditional techniques it would be impossible to assemble the finger as there would be no way to align the pegs with the holes. However, a unique feature of the 3D printing technology is that is allows structures consisting of multiple parts to be produced fully assembled.

The machine produces parts by building them up in layers, printing a new layer on top of the last. It uses two materials, the ABS and a second soluble substrate . The solid areas of the part are printed in ABS but vias (holes) and gaps are printed in the second material producing a block made up of the two materials. Once "printing" is complete the block is placed in a solvent which dissolves the substratel revealing the gaps and holesFigure 4, allowing the joints to move freely.

The resolution of the 3D printing process dictates that no gap can be smaller than 0.17mm. This means if the component was printed assembled this would be the minimum joint tolerance. This gap is larger than could be achieved if the fingers were manufactured as separate parts and it therefore introduces play into each finger. On the prototype finger this play was found to represent a worst case finger tip positional error of ±0.5mm relative to the position measured at the finger joints (i.e. that predicted by a kinematic model). It was felt that this was sufficiently accurate as during object manipulation proprioceptive sensing is used with both somatosensory and visual input. Although at this stage the hand does not include any form of tactile sensing the iCub does include a binocular vision system.

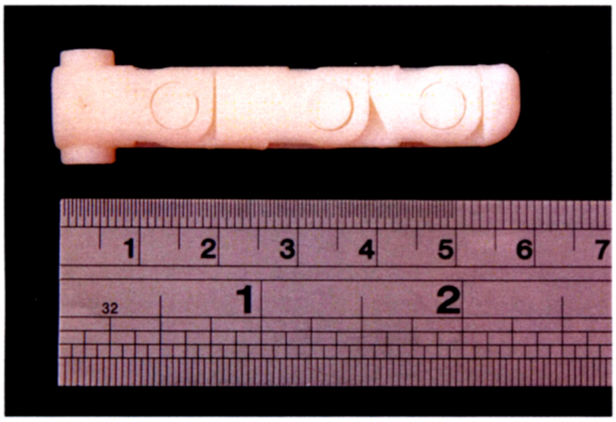

Figure 4 – Prototype finger manufactured assembled.

Due to the small size of the hand it is not possible to place motors and gearboxes at/in the finger joints. Although there is some space available in the palm this is insufficient for more than one or two motors. Due to this all motors are located in the forearm with forces being transmitted to each of the fingers by tendons. The tendon material chosen was Berkley Fireline [ref], this is a polyethylene based braided material with extremely high durability and strength whilst being very fine. The material used on this hand has a diameter of 0.17mm and a tensile strength of 45N.

In order to assess the suitability of the tendon material and the finger manufacturing technique a simple test rig was constructed. This consisted of a single finger, motor and return spring. It allowed the finger joints to be repeatedly cycled to test durability and the finger motion to be assessed. After in excess of 1000 cycles of the finger it was inspected to identify any areas of wear or damage. None were found and the joints appeared to move as freely as at the beginning of the trial. This result increased confidence in the proposed materials and construction techniques. ll paragraphs must be indented.

VII. MOTOR AND JOINT TORQUES

In order to produce a robotic version of a child's hand it is necessary to know not just the dimensions of the hand but the forces that must be generated. This data is extremely difficult to obtain for children of the target age of the robot. The work of Shim et al. studied the Maximum Voluntary Force (MVF) of children aged 6-10 years [1]. This involved measuring the maximum achievable fingertip force for a range of subjects. It was found that for the age groups studied there was an approximately linear relationship between age and MVF. The technique is not suited to very young children as it relies on the subjects following instructions, however, from the data presented it was possible to use extrapolation to determine approximate values for much younger children. It was therefore determined that the MVF of an 18-24 month old child is likely to be less than 1N. This corresponds to a proximal joint torque of less than 50mNm approximately.

Having this data allowsthe motors that are used to power each of the finger joints to be specified. The motors chosen are Maxon RE10s fitted with GP10A 64:1 reduction gearboxes. These motors provide a torque of 70mNm although not all of this can be transmitted to joint torque. It was decided that finger extension would be achieved using springs and therefore some of the motor power would be used to extend the springs during joint flexion. This decision was justified by the fact that the MVF of joint extension is very much lower than for flexion [1].

The same lack of data regarding the wrist torque of children presented similar problems. The wrist serves two purposes, to allow object manipulation and in the design of the iCub to provide a base on which to crawl.

In order to establish the required wrist torques video analysis of a baby crawling was performed. From the video it was determined that the child studied had a maximum hand stride length of 250mm. The hand moved from approximately 125mm behind a vertical line projected from the shoulder to approximately 125mm in front of it. The shoulder to wrist length of an 18-24 month old child is in the region of 300mm and its weight is 12-14kg [13]. Assuming a quarter of the child's weight is supported by each wrist this represents a required wrist torque of 4Nm at full reach. This seems unrealistically high considering the size and age of the child. This hypothesis is substantiated by a study carried out by Jung et al. [15] which determined the maximum wrist force of a group of fit 25 year old males to be 63.59N, equivalent to approximately 6.5Nm of torque. Anecdotal evidence also suggests wrist torque to be much lower than 4Nm. The typical age at which a baby is able to hold their own 4oz (113g) milk bottle is 6-10 months and this represents a wrist torque in the region of 0.1Nm.

It is therefore clear that during crawling a baby does not support the majority of its weight using its wrist joints. Further video analysis showed that during crawling the child either had its palm and fingers flat on the floor or the fingers bent slightly causing the palm to angle slightly upwards. In both cases this means that the majority of the force is applied to the carpals and transferred through the centre of the wrist thus creating very little or no torque at the wrist.

This finding and the anecdotal evidence suggested that a robot wrist torque of between 0.25 and 0.5 Nm should be sufficient to handle the types of object typically grasped by a child of 18-24 months. The motors chosen to provide wrist flexion/extension and abduction/adduction were Maxon A-max16 dc motors with GP16A 157:1 gearheads.

These produce an output torque, which is applied to the wrist via cables, of 0.3Nm.

VIII. SENSORS

In order to allow closed loop position control of the hand, the angle of each actuated joint must be measured. Due to the small size of the robot hand sourcing sensors suitably small can be a difficult. This presented even more of a challenge in this work due to the extremely small scale of the design.

A number of approaches have been used in the past. Butterfass et al. [17] used specially designed conductive plastic potentiometers located at each finger joint. An alternative approach used by Chua et al [16] used linear potentiometers located at the wrist to measure the motion of tendons, from which joint angles could be calculated. Whilst this approach can simplify the mechanical design of the hand the accuracy of the measurements is likely to be reduced due to friction and stretching of the tendons. Non contact systems such as Hall Effect sensors offer much greater reliability and have been used successfully in a number of robot hands [3],[12]. For this reason a Hall Effect based system was chosen for use in this project.

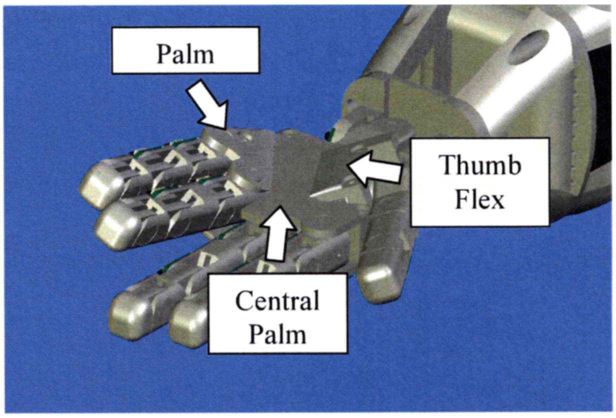

Figure 5 – Joint position sensor

The sensor used is the Austria Microsystems AS5045 12-bit programmable magnetic rotary encoder [19] as shown in Figure 5. A diametric magnet is placed in the centre of the joint pin for the medial phalanx as can be seen. A Hall Effect sensor is then mounted to the proximal phalanx so that it is positioned above the magnet. The same process is repeated for each joint. As the joints move so the magnets rotate beneath the sensors and a change in magnetic field direction can be detected.

IX. MECHANICAL DESIGN

The complete hand and forearm design is shown in Figure 6. All actuators and return springs are located within the forearm and are arranged so as to ensure the forearm is as compact as possible. The overall weight of the hand and forearm is 0.16 kg and the distance from the wrist to the finger tip is 104mm.

Each motor is fitted with a pulley onto which the tendon is wound, converting the rotary motion of the motor into linear motion of the tendon. The arm includes a 2 d.o.f. wrist and to ensure all the hand motions are decoupled they must pass through the centre of wrist rotation. To achieve this, the section of arm between the motors and the wrist is conical, spreading the tendons from the wrist to the motors and springs. This structure ensures that the tendons do not make sharp changes in direction thus minimising tendon friction.

Figure 6 – Complete hand design

The palm is divided into three sections as can be seen in Figure 7. The central palm attaches to the wrist and the index and middle fingers. It also mounts to the palm flex and thumb flex joints which in turn are attached to the remaining fingers and the thumb respectively. Forming the palm from three separate parts means the shape of the palm can be changed by adjusting the angles of the palm flex and thumb flex joints. This allows the palm to adopt a flat position or to form a cup shape as shown in the figure. This ability is in line with a true hand and is used to aid grasping of some objects.

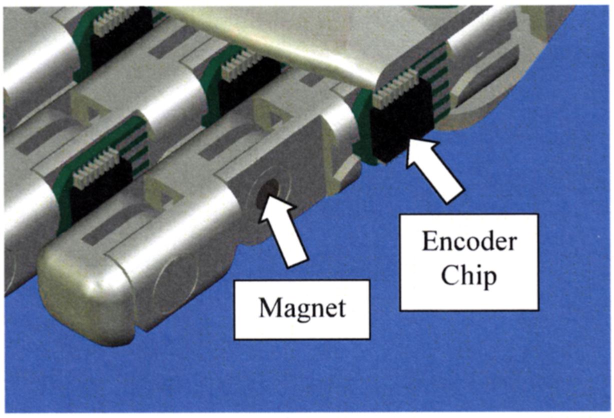

Figure 7 – Palm flexibility

X. CONTROL HARDWARE

The hand is controlled by the existing iCub control hardware and has been designed so that its sensors and motor signals can interface directly with it.

The iCub is commanded from an external control station with high level instructions provided via an Ethernet cable. Power is also supplied via an umbilical. On board the robot are; actuator power drivers, DSP controllers, a PC104 relay station and Pentium based data acquisition cards.

The PC104 card is responsible for communication between the iCub and the external control station. The actuator control electronics monitor sensory signals and generated the necessary control signals to produce closed loop joint position control.

A complete description of the hardware and software implemented on the iCub can be found in [2].

XI. MATERIAL COST

One of the main requirements of the hand was that it be low cost. The fabrication cost alone for the current iCub hand produced using CNC machining in aluminium is in excess of €25,000. For the new miniature hand developed in this work the total material cost of the hand excluding the controller is approximately €3500. Of this €2000 was the motor cost and €250 the price of the joint position sensors. Printing of the mechanical components cost ≈€9 per cubic centimetre of material and this resulted in a total mechanical component cost of €1000.

XII. CONCLUSIONS AND FUTURE WORK

This paper has described the design of a hand for the next generation of iCub robot. It also details the manufacturing technique used in the production of this hand. The current iCub includes a highly dexterous hand but in order to meet the small scale requirements the system developed is under-actuated meaning it is not a true representation of the infant on which it is based. This work has developed a hand with 22 degrees of freedom of which 18 are independently drivable with the remainder being coupled as is the case in a true hand.

In order to meet the low cost, size and weight requirements of the project an investigation was undertaken to determine if the hand could be constructed from plastic. A number of different plastics were considered which had the benefit of low frictional coefficients meaning bearings would not be required thus reducing manufacturing costs. Due to the intricate nature of the design large amounts of machining would be required to fabricate the design and in order to further reduce costs alternative manufacturing techniques were investigated. 3D printing provided a low cost alternative to traditional manufacturing techniques and so a prototype finger was produced from Acrylonitrile Butadiene Styrene (ABS). This prototype was tested to ensure it was sufficiently durable and having proved this a full mechanical design was produced. Future work will complete assembly of the hand and test its performance. Additional sensors, such as tactile or force sensors, will also be considered for future inclusion.

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