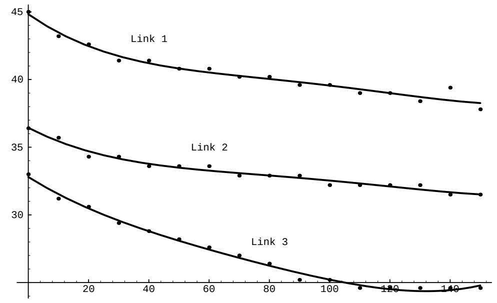

Figure 9: Torque over time for U=20V $\tau[10^{-3}Nm](t[s])$

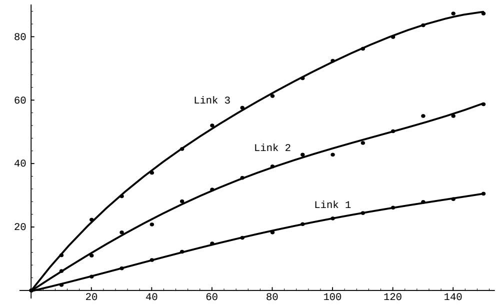

Figure 10: Temperature over time for U=20V $\Delta T[K](t[s])$

6 Conclusion and ongoing research

We have designed and built a direct drive hand that is only about twice the size of a human hand. The properties of the hand have been analyzed thoroughly both theoretical and experimentally. Also a graphics interface has been developed for the hand. The Hall Sensors still need to be mounted to the hand and the conroller hardware is beeing built.

The construction of the hand has given valuable insights to the development of a more precise and human sized direct drive hand. Another even smaller sized prototype finger has been built in our lab. We have begun to construct universal links that will be used for a precision direct drive hand. These links are highly symmetric about the X axis and can thus lead to more accurate modeling and control.

7 Acknowledgements

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We would like to thank Fred Hansen for his suggestions and for the fabrication of the coil form, Luis Arauz and Hong Liu for helping me with the fabrication of the coils, Luis Arauz for assisting in the collection of the measured data and finally for helping me videotape the completed hand. Also we thank Sergey Sokolov, David Max and Bud Mishra for discussions.

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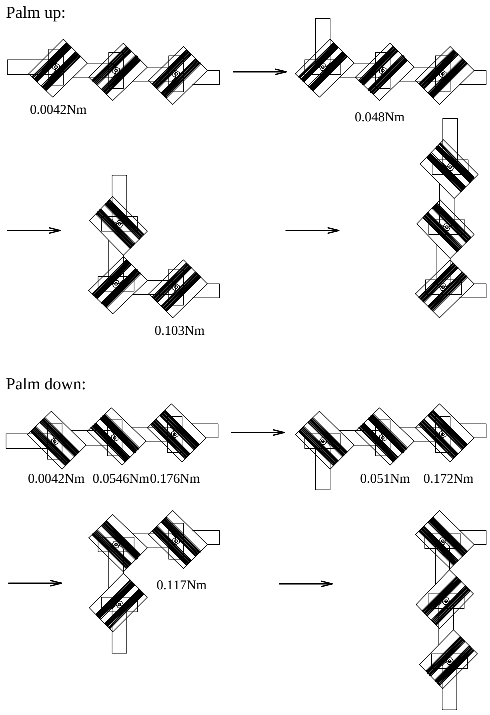

Figure 6: Measured torque requirements

quency is employed for pick and place operations. For instance a complete direct drive robot arm with a 3 dimensional workspace could let the arm swing instead of following a straight line from the pick up point to the put down point.

5 Experiments

We measured the torque of the hand with a Mark-10 force meter and a 12.5cm extension mounted to the tip of the force meter. The measured data tells us the power requirement finger into the horizontal position with the inside of the palm pointing downward. The required torques can be found in Figure 6 This gives us a current requirement of 0.34A, 2.56A and 7.39A for link 3, 2 and 1 respectively which equals 9.0kW for the whole hand. To lift a finger with the palm pointed upward we need have a current requirement of 0.34A, 2.26A and 4.33A respectively which equals 3.4kW for the whole hand.

Experimentally we confirmed that 0.33A and 2.1A are enough for the finger links 2 and 3 respectively to operate the hand at any angle. The amount of current needed for link 3 was not verified due to the high currents involved. Needless to say that the hand can only

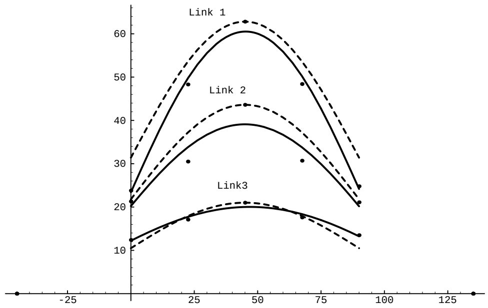

Figure 7: Torque constant $K_T[10^{-3}\frac{Nm}{A}](\theta[°])$

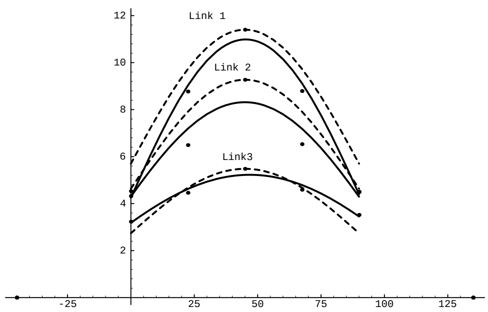

Figure 8: Motor constant $K_M[10^{-3}\frac{Nm}{\sqrt{W}}](\theta[°])$

be operated with such a high current for short periods of time due to the coils heating up. See Buttolo et al. [5] for an analysis of flat coil actuator properties.

However dynamically we need much less power to lift the finger. Experiments showed that a power requirement of 3kW is sufficient to completely close a finger with the palm pointed upward. We showed this by applying 40V with a 15A maximum power supply to the coils of one finger.

In Figure 7 and Figure 8 the thick line denotes a 4^{th} order polynomial approximation of the points given and the dashed line describes the function $K_{Tmax} \cdot \sin^2(\theta + 45°)$ and $K_{Mmax} \cdot \sin^2(\theta + 45°)$ respectively.

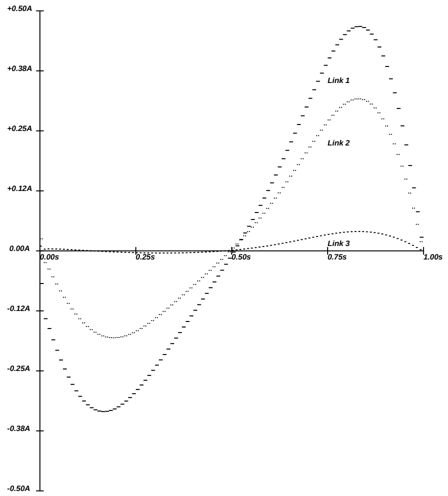

Figure 3: Current requirements to move a perfectly modeled finger from $\theta_i = 90°$ to $\theta_i = 0°$ in one second (gravity vector parallel to Z axis of palm) and an update frequency of 100Hz

which provided adequate stiffness as well as accurate control. Simulations have shown that the computed torque controller we implemented was stable for errors of up to 10% for accelerations and velocities and for errors of up to 5% for torques. Position errors of up to 2.5% gave reasonable results.

The simulation program is also used to give us a graphical output of the current requirements during a trajectory. In Figure 3 the current requirements are shown for a finger which moves from $\theta_i = 90°$ to $\theta_i = 0°$ in one second for a perfectly modeled finger ($e_i = 0$) with the gravity vector parallel to the palm's Z axis. The same movement is shown in Figure 4 but this time the gravity vector is parallel to the palm's Y axis.

We also implemented a fast close hand/open hand trajectory

$$\theta(t) = \frac{85°}{2}(1 - \cos(360° \cdot \frac{3}{2} \cdot t)) + 2.5°$$

which is shown in Figure 5 with the palm's Y axis parallel to the gravity vector. This trajectory does not use the full workspace of the hand to avoid irregularities at angles 0° and 90° where the joints reach their limits. The graph shows that the hand can be used at high speeds with little current in the given configuration.

This suggests that direct drive robot arms may be operated at lower currents if the natural swinging fre-

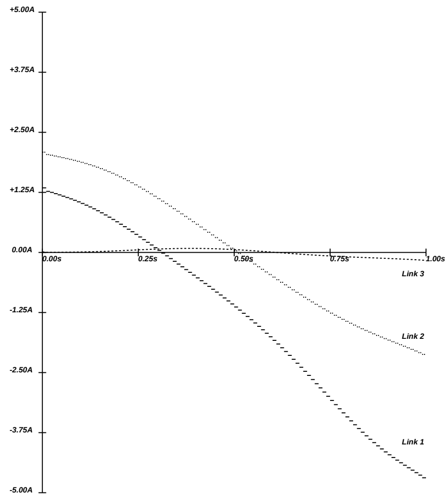

Figure 4: Current requirements to move a perfectly modeled finger from $\theta_i = 90°$ to $\theta_i = 0°$ in one second (gravity vector parallel to Y axis of palm) and an update frequency of 100Hz

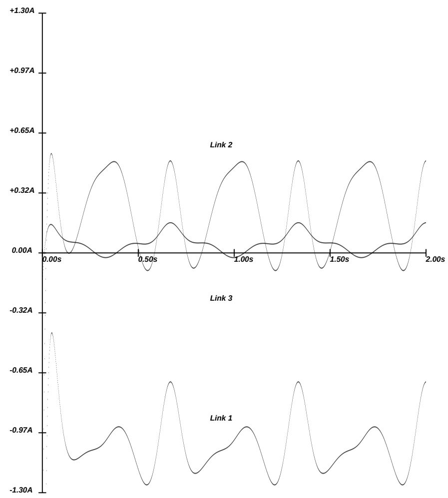

Figure 5: Current requirements to move a perfectly modeled finger from $\theta_i = 2.5°$ to $\theta_i = 87.5°$ and back three times in two seconds (gravity vector parallel to Y axis of palm) and an update frequency of 1kHz (100Hz would give the same result but the graph would not be as clear due to large steps in the plot)

the torque to the joints by changing the magnetic field created by the joints. We can rewrite the above equation as

$$\tau = |B| \cdot |\mu| \cdot \sin(\theta + 45^\circ) \qquad \theta = 0^\circ \ldots 90^\circ$$

Since the magnetic field created by a coil is proportional to the current flowing through the windings of the coil the torque exerted on the magnet inside a uniform magnetic field as a function of current is given by

$$\tau = K_{Tmax} \cdot I \cdot \sin(\theta + 45^\circ)$$

where K_{Tmax} is the torque constant at the maximum.

However since our coils do not produce a uniform magnetic field, we have to include a scaling function to describe the torque as a function of I.

$$\tau = K_{Tmax} \cdot I \cdot r(\theta) \cdot \sin(\theta + 45^\circ)$$

In the case of our actuator we can approximate the function $r(\theta)$ with

$$r(\theta) = \sin(\theta + 45^\circ)$$

as suggested by David Max which gives a relatively close approximation as seen from Figure 7, where the dashed line shows the function $K_{Tmax} \cdot \sin^2(\theta + 45^\circ)$. Depending on the uniformity of the actuators used in the different links, we might consider a different scaling function for each link.

4.2 Finger control

Now that we have the the torque as a function of current we are ready to implement a control algorithm for one finger. We chose a computed torque controller (see An et al. [7]) given by

$$\tau_{ct}(\theta_d, \theta, \dot{\theta}_d, \dot{\theta}, \ddot{\theta}_d) = M(\theta)\ddot{\theta}^* + V(\theta, \dot{\theta}) + G(\theta)$$

with

$$\ddot{\theta}^* = \ddot{\theta}_d + K_v(\dot{\theta}_d - \dot{\theta}) + K_p(\theta_d - \theta)$$

where

θ_d	is the desired position
$\dot{\theta}_d$	is the desired velocity
$\ddot{\theta}_d$	is the desired acceleration
θ	is the position measured with Hall sensors
$\dot{\theta}$	is the velocity computed from sampled position data
K_p	is a 3×3 matrix with position gains k_p
K_v	is a 3×3 matrix with velocity gains k_v

For this controller we get the following error equation

$$\ddot{E} + K_v\dot{E} + K_pE = 0 \qquad \text{with} \qquad E = (\theta_d - \theta)$$

So we should make the gains k_p as large as possible in order to achieve high stiffness and a small steady state error. In order to achieve an over damped system we have to choose

$$k_v = 2\sqrt{k_p}$$

According to An et al. [7] computed torque control and feed forward torque control both give comparable results. However it seems interesting to give experimental results on how computed torque control and feed forward torque control compare for miniature direct drive devices.

We need to apply the following currents to the coils:

$$I = \frac{\tau_{ct}(\theta_d, \theta, \dot{\theta}_d, \dot{\theta}, \ddot{\theta}_d)}{K_{Tmax} \cdot r(\theta) \cdot \sin(\theta + 45^\circ)}$$

4.3 Simulation

In order to simulate the properties of the hand we implemented a 5^{th} order trajectory polynomial $\theta_d(t) = a_0 + a_1t + a_2t^2 + a_3t^3 + a_4t^4 + a_5t^5$ with the constraints $\dot{\theta}_0 = 0, \quad \dot{\theta}_f = 0, \quad \ddot{\theta}_0 = 0, \quad \ddot{\theta}_f = 0$ where θ_o is the initial position and θ_f is the final position.

A 5^{th} order trajectory polynomial has an advantage over a 3^{rd} order polynomial because when the finger moves from $\theta_i = 0^\circ$ to $\theta_i = 90^\circ$ maximum accelerations occur at angles of $\theta = 6^\circ$ and $\theta = 84^\circ$ whereas for the 3^{rd} order polynomial calls for maximum accelerations at angles $\theta = 0^\circ$ and $\theta = 90^\circ$ where we have the least torque available.

To simulate the dynamics of the hand we calculated the dynamics of the hand according to our model which included the error functions e_τ, e_a, e_v and e_p for torque, acceleration, velocity and position. The error functions e_τ, e_a, e_v give a random output that lies within a preset percentage of the input. The error function e_p changes the input for up to the preset percentage of 90°.

$$\begin{aligned}
\ddot{\theta}(t) &= e_a(M^{-1}(\theta(t)) \cdot \\
&\qquad \left[e_\tau(\tau) - V(\theta(t), \dot{\theta}(t)) - G(\theta(t))\right]) \\
\dot{\theta}(t + \Delta t) &= e_v(\dot{\theta}(t) + \ddot{\theta}(t)\Delta t) \\
\theta(t + \Delta t) &= e_p(\theta(t) + \dot{\theta}(t)\Delta t + \frac{1}{2}\ddot{\theta}(t)\Delta t^2)
\end{aligned}$$

To simulate control of the hand we set the position gains $k_p = 1000$ and the velocity gains $k_v = 63.2$

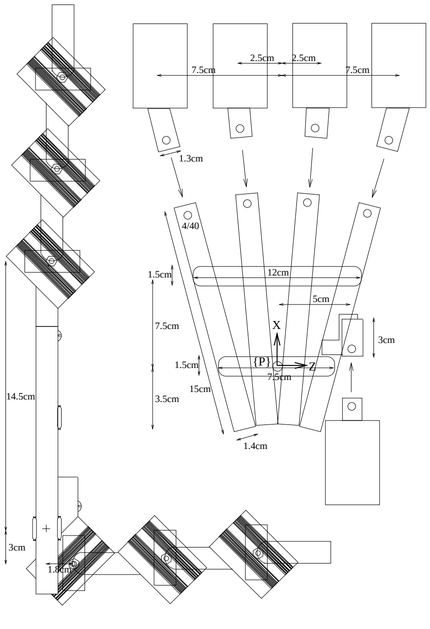

Figure 1: Side view of hand and top view of palm

- **Heat** The coils use for the hand heat up very fast due to the high power requirement. So the hand can only be operated for short periods of time with out overheating the coils. Needless to say that the hand may not be used in an environment were temperature needs to be precisely controlled (e.g. for laboratory experiments).

- **Low Torque** Since we still have the problem of overheating the coils to achieve high torque, the hand may only be operated with relatively low power. This in turn leads to low torque. The hand is not able to support itself if it is powered according to its heat constraints.

We refer the interested reader to Mason et al. [4] who give a more extensive survey about existing artificial hands, and to Hollerbach et al. [8] who have analyzed actuator technologies for robotics.

2 Design

The design of the hand is according to Figure 1 which gives an overview of the sizes involved and also shows how the fingers are arranged. Link 1 of the thumb is closed in the side view of the hand.

3 Inertia tensor model

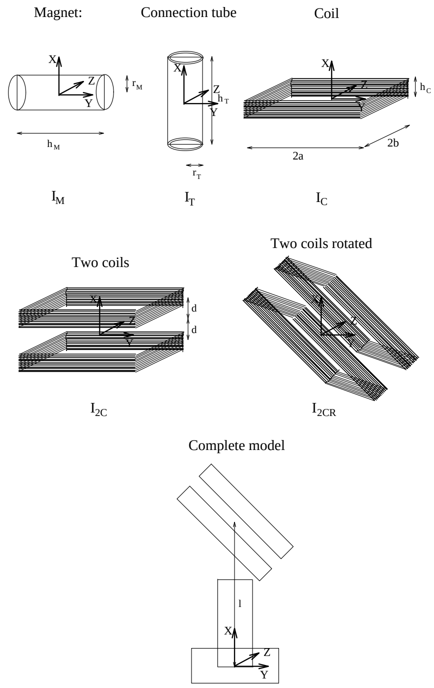

Figure 2: Inertia tensor model

We use the following approximation to model the inertia tensor. One finger link consists of a magnet tube, a connection tube and two coils as seen in Figure 2. See Craig [3] and McKerrow [6] for modeling of robot manipulators and for theoretical background.

As one can easily see from the modeling process, a high degree of symmetry around the X axis is desirable. The better the model used, the more accurate the control algorithm will be. From the dynamic equations below we can see that in the case of a symmetric link the only two parameters to adjust are the center of mass for each link and the zz-entry of the inertia tensor in order to achieve a more precise control. However no link can ever be precisely manufactured. Thus small inaccuracies remain.

4 Hand control

4.1 Direct drive actuator control

The torque of a magnetic moment inside a magnetic field is given by

$$\tau = B \times \mu$$

In our case let the magnet inside the magnet part of a link have the magnetic moment μ and the coils around the joints create a magnetic field B. Thus we control

A direct-drive hand: Design, Modeling and Control *

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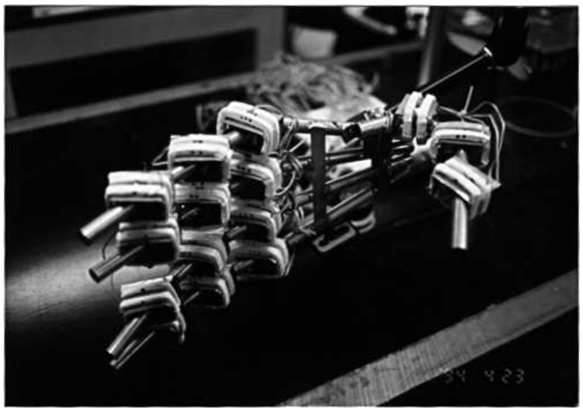

Abstract

An artificial 15 degrees of mobility direct drive hand, slightly bigger than a human hand, is presented. Advantages and limitations of a direct drive hand are given. We introduce our design of the hand and present a model for control of the hand. Finally we describe our experiments with the hand. The direct drive hand dynamics have been simulated and the control algorithm has been tested on the model.

1 Advantages and limitations of a direct drive hand

The Utah/MIT Dextrous Hand and the Stanford Hand are very small, compact and very human like. However instead of using tendons we have used miniature direct drive actuators recently developed [1], [2]. With our approach, we try to make use of the following properties of direct drive technology.

- **Speed** As a result of the low response time, the hand will be able to simulate the flexible, fast motions of the human hand quite accurately. This allows the simulation of many human abilities that require high speed motions such as playing a piano or typing at a keyboard.
- **Low cost** Due to the use of inexpensive material the hand can be produced at very low cost. The brass material as well as any screws, nuts and the like used, adds up to roughly $20. For the complete hand one also needs 85 magnets priced at about $3.50 each which gives a total cost of about $320 (excluding any additional hardware and assembly time needed).
- **Overall Size** The overall size for the hand is quite small. The only other devices required other than the hand itself is the power supply and the control circuits. Tendon actuators are still quite large and occupy considerable space.
- **Dynamic model-based control** Since the hand will be operated at very high speeds the dynamics of the hand have to be modeled accurately in order to achieve precision control. Centripetal and coriolis terms may no longer be neglected.

However the direct drive hand also has its limitations:

- **Large Power Requirement** The power requirement for the hand is considerable. For our hand we require roughly 9kW to operate the hand at any orientation, which is way to much to operate the hand because of safety requirements and overheating in the coils, although further miniaturization would also decrease the power requirement.

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