Modular bio-mimetic robots that can interact with the world the way we do

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***Abstract*— The study of human sensorimotor control and learning through robotic devices requires systems that possess bio-mimetic characteristics that allow them to interact with the world in a similar fashion dynamically (this includes backdrivability, high bandwidth, implementability of complex control algorithms, force feedback, low friction, low inertia, robustness, autonomy, appropriate strength to weight ratio in the case of locomotion, safety, among others). Traditionally, engineered systems have evolved based upon industrial requirements, which are quite different. From the context of studying and mimicking the way humans perform control of their bodies, we state that there are specific groups of characteristics that are essential for use in researching sensorimotor control and learning. Designing robotic systems from this perspective necessitates solving new constrained design challenges that integrate with, adapt, and improve upon known approaches. A new design for a bio-mimetic backdrivable modular robot finger which addresses these challenges is presented. Results are presented demonstrating its effectiveness. The novelty of this robot is not only in the integrative design approach, which meets all the constraints presented without compromise, but also as the first bio-mimetic robot to integrate modularity, and it is highly compact. Additionally, the system has the capacity and bandwidth to run real-time control algorithms that can eventually model human behavior and perform complex manipulation tasks.**

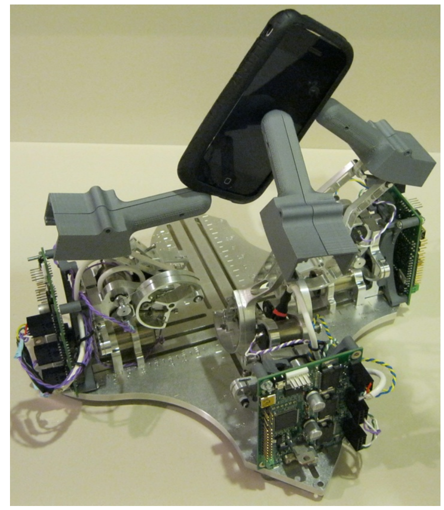

Fig. 1. The bio-mimetic backdrivable robot discussed in this paper. Each module is approximately the size of a human finger, and includes all electronics onboard for communication, processing, and control.

I. INTRODUCTION

Recently, scientists and engineers have been studying sensorimotor movement and learning (movement in biological systems which uses sensors and actuators) with the goal of developing not only a model of coordinated biological movement itself, but also a more complete accurate model of how biological systems interact with and learn from the world. These efforts began with the first influential model of sensorimotor learning in [2], and have evolved to include computational approaches centered around optimal control[25][22] and, where learning is concerned, optimal estimation[19][5][12]. Biological systems solve the problems of locomotion and manipulation with seeming ease, as well as problems of redundancy[15][26], and so, as we work to develop more advanced robotic systems which must intelligently interact with their environment, including humans, it is reasonable to study how biological systems solve these problems.

In addition, an understanding of sensorimotor movement and learning in biological systems will lead to improved rehabilitation therapies, more natural artificial limbs which can detect intention and act accordingly, sophisticated artificial systems which can solve challenging problems involving active learning[19], solutions for individuals who cannot, through injury or disease, control their bodies, and more mobile robotic systems which can navigate environments dynamically in ways that current robotic systems simply cannot. In fact, there are essentially no dynamic bio-mimetic robots currently available simply because people are approaching the problem with the wrong tools (or they fail with a primary characteristic, such as bandwidth or backdrivability).

The aim of this paper is to present methods which address, expose, and integrate solutions to several of the challenges of designing and controlling a modular bio-mimetic robotic system. A design (Fig. 1), the ModBot Finger (MBF) is presented which possesses exceptional unique characteristics appropriate for bio-mimetic control. It is the first dynamic bio-mimetic backdrivable robotic device which is also modular.

A system must possess a synthesis of key features in order to create a bio-mimetic robotic system appropriate for sensorimotor movement and learning studies. Robotic designs provide a unique challenge in that they incorporate aspects of different disciplines. Topics which must be carefully addressed are not only the mechanism, but also the sensors, actuators, and drive system. The joints must be low friction, low inertia, backdrivable[1], robust, high bandwidth mechanically, with appropriate joint ranges, appropriate low mass, stiff, precise, and possess the capability of generating the right amount of force (depending on what the device is to be used to study). In addition, the electronics to drive the actuators and read the sensors must be incorporated. These electronics must be controlled by an embedded processor, a network of processors, or communicate with a host processor such as a PC or cluster of computers. These hardware

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[1] A system is backdrivable if the system can not only apply energy to the external world by changing its state, but the external world can apply energy to the system and alter its state.

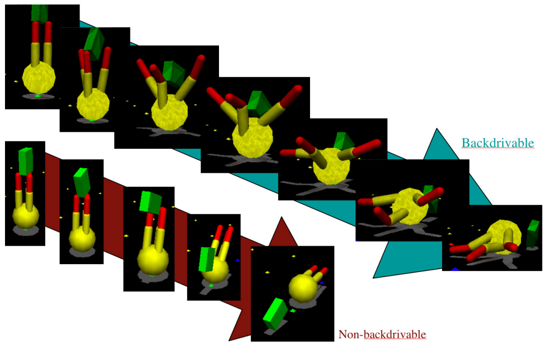


Fig. 2. This depicts a simulation of the dynamics of a block colliding with a multi-jointed system. One system is backdrivable, the other is not. The two systems interact with the environment in fundamentally different and complex ways. It is difficult to force the non-backdrivable system to behave in the same way as the backdrivable system.

components must be able to communicate information, either through analog signals, or digitally through some serial or parallel communication, at an appropriate rate (i.e. data bandwidth). If locomotion is to be studied, or the mechanism is to be moved (such as in the case of a hand), the electronics must be small enough for the system to be autonomous. The wires connecting the actuators, sensors and power sources to the electronics must be routed through the system in such a way that the movement of the device is not impeded, and the cables will not break under repeated cycling. A control algorithm must be devised which coordinates all the requisite hardware and sensor information, performs mathematical operations, perhaps even simulations of the physical world and predictions into the future in better than realtime. If the system has many degrees of freedom (DOF), which most biological systems such as humans do, the bandwidth and mathematical processing capabilities of the system must be very high.[2] To address one aspect of these design issues while ignoring another leads to a design which, though it solves some problems, may be inadequate for the research required to elucidate the mysteries of biological sensorimotor control. Most robotic systems which have been developed lacked parallels to biological systems at a fundamental design and control level (see Fig. 2), and are therefore limited in their applicability to developing models of biological systems as well as control methodologies which are consistent with such systems.

There are many robotic systems which can mimic the appearance of a biological system, and, if suspended in the air by a cable (or provided an unchanging environment that matches the trajectories) may follow joint trajectories captured by motion capture data, but these robots often lack the strength, backdrivability, bandwidth, or other bio-mimetic characteristics required to be useful in such research[29][7][14][11][17].

The issue of backdrivability is another key aspect to studies in human sensorimotor control. It is important to determine not only a piece of the biological control methodology, but rather an inclusive model which unifies different control modes. Traditionally, researchers have separated power-type grasps and manipulations from fine grasps and manipulations. Thus there is a split in the type of robot design in bio-mimetic systems. Some researchers believe that a design need not be backdrivable in order to be used for sensorimotor control research[3]. One workaround is to assume that only the finger tip matters (the end-effector) during interactions with the environment. Therefore, the fingertip only needs to appear to be backdrivable. This can be achieved by compliant control methods[1], where the force at the endpoint is controlled. Though there are situations where this is effective, these methods provide an incomplete picture to the artificial system. That is because a realtime simulation must be run at every timestep, simulating the desired dynamics of the robotic system, and applying energy to the system to effectively alter the system dynamics to approximate the ideal system. There are several issues with this approach. The first is that the simulation must be very fast, as must be the overall control loop. There is always some lag, but if the system bandwidth is extremely high, this lag is small. A tradeoff would emerge as to safety regarding a very high bandwidth system which is not actually backdrivable. The system would have to be capable of exceptionally high forces in order to produce the requisite accelerations to approach a true system. The second major issue is that, for many sensorimotor tasks, the tip of a finger is not the only important area where backdrivability or compliance is necessary. Then every surface must be instrumented with precise touch sensors which provide high resolution force vector information. This becomes a difficult high dimensional signal processing problem very quickly, assuming that an appropriate touch sensor even exists (which it does not at the time of this writing). It is quite difficult to create surfaces which are completely instrumented with touch sensitivity everywhere. MEMS is a promising technology for this issue. Eventually, surfaces will be able to be painted with microscopic force sensors, but this approach is still in its infancy. Even so, the ultimate differences between simulation and reality, and the limitations due to bandwidth of the robotic system, as well as the inner force control loop constantly having to apply energy to the system in order to simulate passive dynamics would lead to structurally different and expensive (energetically) control algorithms than those used by biological systems at a fundamental level.

Similarly, some designers use compliance to create robots safe for human-robot interaction, such as DOMO[4]. This type of design uses springs at some point in the actuator mechanism to create some degree of compliance. Compliance is to be differentiated from backdrivability in that compliance, as the term is used here, refers to systems which can have differences imposed between actuator side and endpoint side by the external environment. This does not denote a bidirectional information flow necessarily, though such a bidirectionality can exist. In fact, such elasticity can introduce nonlinearities which are highly undesirable from a control standpoint, and would not be controllable in the sense that an elastic component has particular properties. What if one needs to perform an experiment with variable elasticity or where the elastic element should be controlled? This is not possible or is highly nontrivial if one has a 'static' spring element in the system. We can control stiffness and elasticity at the actuator side because of the direct connection between the actuator and output of the joint.

Some work has been done to quantify theoretical design methodologies for the many types of 'tendon' driven mechanisms[16], but most of these concepts have been part of engineering methodologies for other drive systems for

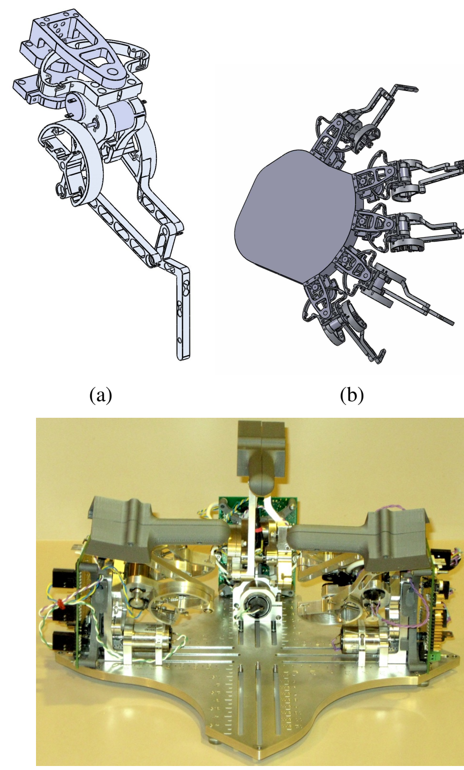
[2]Consider five 3-DOF fingers, each of which outputs 3D force and position values, motor currents, motor voltages, and takes in commands for 3D position and force at minimum, among other commands such as adaptive parameter changes, and possibly more data at 1kHz. As 16-bit values, this would mean each finger would have to be in bidirectional communication with a master CPU at a minimum of 288kbps. Over five fingers this is 1.44Mbps, which is beyond most standard protocols for serial interfaces. Packet-based methods must be used with extreme caution in situations where realtime control is being attempted. Many of the robots currently in existence have many more degrees of freedom than this example, it is clearly very important to avoid information flow bottlenecks.

decades. The challenge in creating functional cable drives is not only the theoretical logic, which gives the beginning of the design, but also the science of practice, which is addressed here.

A byproduct of the design approach presented in this paper is that it can be used to study locomotion, manipulation, and virtual reality interaction. Since the robot is modular and autonomous, it can be reconfigured to form multi-pedal robots, various hand configurations, robots with changing limb quantities, and since they are also wireless, they can be configured to be perturbation objects for experiments, and more.

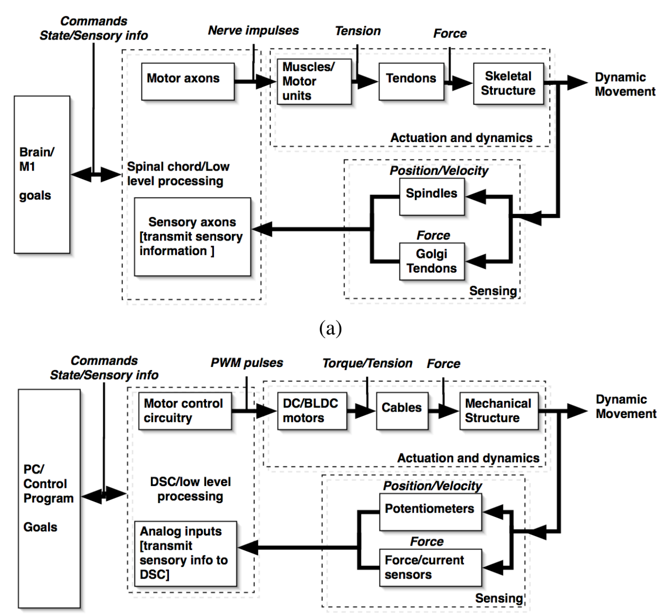
Though this is not the first robot to include some modular component, it is the first dynamic, backdrivable bio-mimetic robot to incorporate modularity. The modular characteristics of this robot must not be under-appreciated. Consider one is interested in studying (and creating in a robotic setting) the dynamic locomotion of dogs, cats, spiders, rats, humans, and even some creatures which do not exist, such as tripeds. Additionally, one would like to develop a control for one then apply it to another and consider the implications of the effects. This could easily be done in the context of this robot. In fact, one could use an adaptive algorithm to generate a controller, then remove a limb and note the effects on the control system. This would be exceptionally difficult in the case of other systems - one would have to change the code to work with different hardware, possibly develop (over the period of years, it should be noted) new robots for each application. Here, new experiments can be created and performed very quickly with minimal effort.

The rest of this paper is organized as follows. In Section II, the overall design approach is presented. Section III presents results and computations demonstrating effectiveness of this approach. Finally, Section IV concludes the paper with some remarks, a discussion of future works, and a summary of the main contributions of this design approach.



(a) (b) (c)

Fig. 3. Isometric view of (a) the MBF. The robot was designed first in a parametric modeling package and tested in order to meet mechanical load requirements before production. (b and c) shows the modularity of the MBF, as it is assembled into a hand simply by attaching five modules to a base, or three in the photographed example.



(a)

(b)

Fig. 4. Inspiration for the overall system architecture in our designs (b) was drawn directly from the main components of the human sensorimotor control loop (a).

II. Design

The final design is shown in Fig. 1 and 3(a-c), and Fig. 3(b, c) shows the modular nature of this design with examples of assembling hands.

A. *Design inspiration*

The design begins with the simple question : how can we design a bio-mimetic robotic finger? The requirements follow naturally from this initial question. We then use standard engineering methods to analyze, and model biological systems, in this case we will use a human being's sensorimotor system (See Fig. 4(a) and 4(b)).

The overall components of the sensorimotor system within our model consist of the Brain/M1[3] which communicates bidirectionally with the spinal chord. The spinal chord contains motor axons which send motor commands to the muscle motor units, while integrating sensory information and performing some low level control. [4] This 'block' sends signals in the form of pulses to the muscle motor units (see [10] for a good overview), which in turn produce a tensile force upon the tendons they are connected to. These tendons then apply tension forces to the skeletal structure to which they are attached, which brings about dynamic movement. This movement is fed back into the control system by sensors

[3]M1 being the primary motor cortex, an area of the brain in the posterior portion of the frontal lobe which, in concert with the pre-motor areas, plans and executes coordinated movements in humans and some other biological systems.

[4]It should be noted that there is disagreement about the sensorimotor system structure and behaviors, but this is one of the standard models[23].

integrated into the motor units in the form of muscle spindles and Golgi tendon organs that react linearly with force.

Thus, in creating an artificial system, we refine our design problem at the first iteration (more will come as we develop our statements further) to note that we require a controller, sensors, actuators, and a mechanical system coupled to the actuators which has the appropriate DOF for a finger or a leg (if we wish to study locomotion in addition to manipulation).

Next, we refine our parameters to ask what kind of control system is needed. In following the structure of the sensorimotor system, a hierarchical control system is required. It needs a high level controller capable of massive computations and complex planning (from which the goals are produced), and a low level controller which can perform some computations and communication. The low level passes information bidirectionally through the system to the high level (and passes commands to the low level). This low level controller needs a high bandwidth in order to be capable of signal processing, coordinating the many DOF which it will be required to control, and communicating with the higher level controller. It will also need to translate logic level motor commands into some form of approximation of an analog signal to the actuators - in the model's case, DC motors. The biological system does it with pulses, our system uses pulse width modulation (PWM).

Our system will need sensors to make measurements, and feed back position, velocity, and force, as the biological system, which we desire to mimic, contains sensors that estimate each of these quantities. In our artificial system, position and velocity at the joints can be measured using highly compact potentiometers. These provide an absolute position measurement (similar to human physiology), and can be differentiated numerically to create a measurement of velocity. The signals are very low noise and, since they are analog, can be sampled at a high rate and averaged to provide a superior measure of position and velocity. Other position measures were considered, but lack some appropriate conditions - for example, encoders are not small enough, lack required resolution (when of minimal size), or are relative. At the scale of a human finger, a load cell connected through the drive system is impractical, and creates a lack of stiffness in the system, which leads to undesirable nonlinearities. Mountable touch sensitive surfaces currently provide too poor of a measurement fidelity for manipulation tasks. The same measurements can be achieved by integrating a three dimensional force sensor into the structure of the mechanical system. This has the advantage of clearly separating the x, y, and z axes.

As discussed in the introduction, an often overlooked but central aspect of biological systems for creating an artificial system that will be useful for understanding dynamic coordinated biological control is the bi-directionality of information flow and interaction with the world. Many engineered systems are highly precise but due to some design weakness[5], they will not generate answers to the question of how biological sensorimotor control works, and how we can model (and recreate) it. This is where compliance, passivity, and backdrivability in the mechanical design come into play. These features are crucial (See Fig. 2), and determine the drive system choice. We will not use compliance control, instead opting for making all design choices such that the system has superior passive dynamics (including in the drive system).

This defines the overall system design problem, but several specific questions must be answered in general when creating a bio-mimetic robot:

- How should the overall mechanical structure be designed?
- What kind of drive system should be employed?
- How much mass, inertia, and strength does the robot require (or is allowed)?
- What is the desired bandwidth (or minimum bandwidth)?
- Given the constraints, what kind of digital hardware is required (microprocessors, desktop workstations, methods of communicating information, etc)?

The following subsections present certain aspects of the robot design and its significance in general bio-mimetic design methodologies. Though we are presenting our design, we also emphasize that this demonstrates the constrained design integration which must be addressed for a bio-mimetic design to be successful. Thus these sections discuss how to address these problems (such as friction, system bandwidth, or inertia) which can hamper the effectiveness of an otherwise great design.

B. Mechanical Structure,

While it is true that, eventually, it will make sense to control a bio-mimetic system which mimics the structure of biology in close detail (such as a mechanism like the ACT hand[28] which attempts to replicate the kinematics of the bone structure of the human hand, as well as the tendons, the level of complexity of this type of system is very high, and it is entirely specific to one biological system only - the human hand[6], so multiple varieties of experiments would need separate hardware to be developed, as mentioned in the introduction. Thus, a starting point is needed which provides a system that is robust, can be arranged for multiple types of experiments and to mimic different biological sensorimotor structures, and can be easily manufactured, assembled, and used. A device is required which can be used fearlessly. Our ModBot devices serve as intermediaries between overly simple robots which do not mimic biology, and robots which are perhaps too complex to start with (and still have some lacking) from the control perspective.

The problem then is the following - *Design a structure which satisfies the following constraints:*

- Has the appropriate DOF and joint ranges for manipulation
- Has appropriate friction properties (i. e. minimal)
- Has the appropriate mass and inertial properties for locomotion and manipulation (i.e. minimal)
- Cannot break itself (and if it does break it is inexpensive and easy to fix), and can withstand manipulation (MBF)
- Is reconfigurable for multiple experiments easily
- Can be mass-produced

*1) **DOF and Joint Ranges**:* The human finger[6] has four rotational DOF (the fourth distal phalangeal joint - DPJ - is highly coupled, and not necessary for many manipulation tasks; it would also be easy to provide an optional tip for either robot which would possess an active or spring-actuated passive fourth degree of freedom). The MBF has three DOF. The workspace of the MBF is roughly that of the human finger (Fig. 5(b)).

[5](from the perspective of sensorimotor control studies)

[6]This system is still being developed, and lacks the robustness for experimental control systems. It is very easy to break, and very time consuming to fix. It is also not clear that the hardware used in this system has the requisite bandwidth or drive system design for passivity as discussed in this paper, though the motors are capable of high forces.

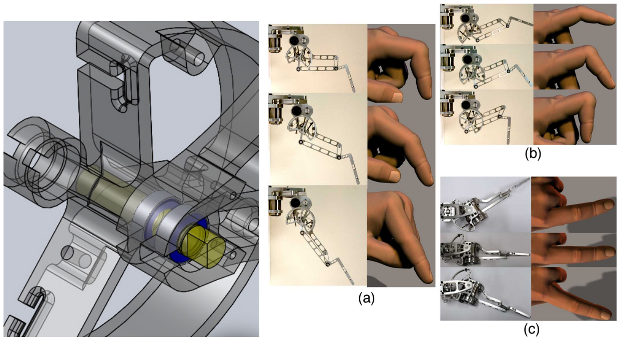


Fig. 5. (Left) A close-up CAD image of the double-bearing cantilever shaft design. The image sequences in (a), (b), and (c) show various postures of the human and MBF. The sequence in (c) is a top projection.

*2) **Friction**:* Friction causes nonlinearities, unexpected behavior, and biological systems tend to have very minimal friction. Thus, we desire to minimize friction, and set a requirement that the dynamic friction must be less than one order of magnitude smaller than the maximum force (a comparison is made in the results section). A double-bearing/cantilever shaft with press fit design was created to facilitate minimal friction (Fig. 5, left). ABEC-7 rated ball bearings are used for high precision, low friction, high stiffness, robustness, and high bandwidth.

This joint design minimizes friction effects. A joint allowed to free-swing will continue to do so for significantly more than one minute before coming to rest (See Table I for a summary of friction experiment results).

*3) **Inertia**:* The inertia of the robot was minimized by keeping the inertia of the motors used to a minimum, and by placing the mass near the center of rotation as much as possible. An iterative design-and-analyze method was used with structural analysis software and parametric modeling to remove material without sacrificing strength. The MBF's moment of inertia is quite low, as much of the mass is at the base, and most of the motor mass is not coupled into the moving components. For manipulation, inertia should be minimized in order to probe objects more sensitively.

*4) **Size/mass/force requirements**:* The approximate size of the MBF was determined by the length of an average human finger (the final size is slightly larger so that electronics and motors may be included on-board). For manipulation experiments and haptics, it is useful to be capable of producing approximately one Newton at the endpoint.

A large factor of safety regarding robustness was desirable as most biological joints have a large factor of safety regarding their standard uses, so since on the order of a few Newtons are required loads and force capabilities, all joints and components were designed to withstand 50N of load in all directions of interest.

Here we require minimal mass, high torque-weight ratio, and minimal inertia if the robot is to be used for manipulation and if it is to be backdrivable. Small DC brushed motors are employed for ease of control and low rotor inertia.

Various candidate materials were considered during the design phase. Given the type of design, and issues of robustness and manufacturability, as well as strength to weight ratios, 6061 aluminum was ultimately selected. Aluminum axles were designed with C-clips to retain their position.

The joints themselves, in each dimension, are very stiff in all orthogonal directions but the degree of freedom (which is very smooth and passive), with no perceptible play in undesirable directions. This is because we want to control stiffness at the algorithmic level (with actuators), rather than build a static elasticity into the system (ie with decoupling the load from the actuators). This also serves to make the joints more orthogonal regarding how forces are transmitted, and facilitates measurement and control.

The mass of the MBF with electronics and all cabling is 207.6g (See Table I).

*5) **Modularity**:* The system modularity consists of a standard mechanical mounting pattern of three bolts, and essentially of the rest of the robots being self-contained (assuming a small power source is onboard or two wires are connected to a robot through a removable cable which can be attached to the base mounting point. The electronics are all at the scale of a single module, and are incorporated.

C. Drive system - Cable drive and backdrivability

Biological systems (with a skeletal frame) use tendons connected to muscles and the skeletal structure in order to exert forces on the system. This is similar in drive technology to the cable drive.[7] The cable drive transmission methodology can be superior regarding friction, backlash, and backdrivability. In order to interact with the world in a way which simulates by its nature biological systems from the perspective of control, a system which can not only act in the world but can be acted upon by the world with a resulting change in state is needed. The definition given previously for backdrivability leaves out the fact that it is really a matter of degree. Some belt and gear transmissions can be back-driven, but friction and backlash bring about unpleasant nonlinearities which interfere with ideal models and results. Biological systems tend to be highly backdrivable and as such the internal control systems within a human probably neglect things such as backlash and friction.[8] In a control sense, the characteristic of backlash would create difficult to predict nonlinearities, friction, and other issues (for a biological and mechatronic control system). Thus if attempting to mimic the characteristics of the structure of biological control systems and intrinsic behavior as a result, it is appropriate to mitigate the characteristics of friction and backlash in the robot design, as nature has done. The basic components of a cable drive consist of a pinion shaft, a spur shaft, a high flexibility cable, a means of constraining the cable in place, a way of tensioning the cable, and a way of constraining the pinion and spur wheels or surfaces such that they can only rotate, and resist the force due to the required tension in the cable. A spring is not necessary as the cable itself acts as a stiff spring.

D. Circuitry

Identical circuitry is used for the MBF (custom built for this application). These circuits implement a high performance embedded system which is capable of driving four DC motors (brushed or brushless) for the MBF, estimating unknown system parameters via an Extended Kalman Filter[18][20], reconstructing position estimates of the joint from the analog potentiometer joint sensors, filtering digitally all analog signals, and communicating either with a higher level processor, over USB to a PC, or wirelessly through the installed bluetooth link with a PC, another robot, or any bluetooth-enabled device. The processor boards can also communicate with most standard serial protocols - ECAN, SPI, UART, I2C, and more. The maximum data rate is set

[7] Though the cable drive often translates rotational into linear motion, the idea of a pull-pull system of actuation is parallel.

[8] It would be very disturbing indeed if the reader engaged in a hand shake with a friend and the other person's arm had intermittent and sudden resistance to the shaking motion, and when the resistance occurred it gave a sense of thick viscosity!

by the communication device (the slowest component in the system) at 3Mbps. The question of how much (mechanical and data) bandwidth is needed reduces to what the human (or other biological systems of interest) bandwidth is. The human perception/action sensorimotor control loop has been measured to be approximately 30Hz. Therefore a digital control system should run at 20 times the desired bandwidth, which would be a minimum of 600Hz. We may wish to perform operations at 'superhuman' speeds, or study biological systems which possess higher bandwidth, so we set the bandwidth requirement to 1kHz. Even the bluetooth speed is more than enough for the high level loop to operate at over 1kHz (an internal feedback loop has been run at 40kHz successfully). The drive circuitry is capable of controlling a 5 Amp load at 12 Volts, so design changes in the future can be accommodated without changing the circuits (and costing time). Each board also has an onboard power supply to regulate an input down to 12 Volts so the performance of the motors does not change with a battery's changing charge state.

Each board has 24 analog inputs with 12-bit resolution. This gives a position resolution of 0.08 degrees[9].

The circuits are quite compact, integrating everything on one board with dimensions under 8cm wide by 6cm long (smaller than the palm of the average sized male hand), with a thickness of under 1cm, and are directly mounted to each robot module.

E. Control

Decentralized proportional integral derivative (PID) control[1] combined with online efficient computation of the inverse kinematic solution[8] to reference tracking (force or position) in cartesian space was used for initial experimentation. The passivity experiments were performed in open loop (a command is given to the finger which precisely cancels gravity at the horizontal level, then when we add masses, the effect of the backdrivable transmission can be immediately seen). Each motor is driven by a local feedback controller with an estimator for unknown parameters, and a higher level controller handles communication and more complex control strategies.

Ultimately we will be implementing a Model Predictive Nonlinear Hierarchical Feedback Control scheme based upon our earlier iterative linear quadratic control (iLQG) method, which is a local method, combined with another of our works which uses function approximation to create an estimate of the globally optimal control[27][13][24]. The global control is used to initialize the local control at each timestep, and is precomputed ahead of time. In the realtime portion of this scheme, there is a high level control which plans trajectories and generates the reference, and a low level control whose job is to push the system to behave as similar to a point mass as possible. This is discussed further in [21].

III. Results and Discussion

The passive dynamics and backdrivability of the robot are key, and therefore will be discussed first. An external disturbance acting on the MBF is directly felt at the actuators and indeed causes a change in state. The robot can be back-driven at any joint during behaviors, as the cable drives do not suffer from friction lock or backlash, as gears or timing belts would. Though some researchers have the perspective that the load should be decoupled from the actuator[9], and thus would consider our more direct connection a negative, this is now a controllable compliance, and allows for greater flexibility. This is only possible with this type of drive system - a gear or belt-driven system would have too much friction and backlash for this to be possible, and would introduce difficult to model and predict dynamics/nonlinearities.

TABLE I

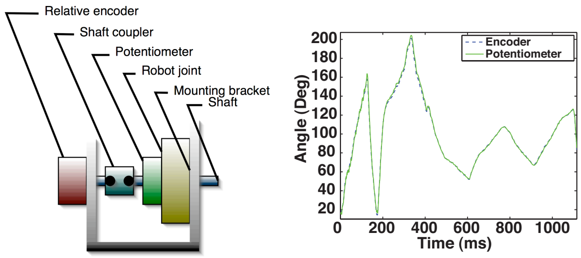
Force production capabilities (at the middle of the workspace), backdrive forces (Linear forces required to backdrive each degree of freedom from the endpoint of the robot with the motors not powered. The robot was oriented for each test to remove gravity from the measurements), maximum average velocity (obtained by differentiating position measurements and averaging over several samples), inertia about each joint, and mass of the robot.

	x	y	z
Endpoint Force (mN)	736	528	2894
Backdrive Force (N)	2.94e-2	5.89e-2	2.94e-2
Max. Velocity (m/sec)	49.5	42.3	60.1
Interia, joints 1-3 (kgm^2)	7.4e-4	2.7e-5	2.7e-5
Mass (g)	–	–	207.6

The force required to move the joints from the endpoint in each axis (orthogonal to gravitational forces) is given in Table I. The experiments were performed using a calibrated force sensor moved along a linear slide at a constant velocity by an actuator, with one end attached to one side of the sensor, and the other side attached to the robot with a light cable such that forces (in a single axis) acting upon the sensor were measured as it moved the (passive) robot joints through the range of motion for each axis at a low velocity (to avoid inertial effects). The average force value was recorded and thirty repeated tests were performed, with the average taken as the measurement to report. It is clear that the friction design goal is met, as all values are significantly less than an order of magnitude below the force capability of the robot (compare to the Delta Haptic robot, which has a dynamic friction of approximately 3N, where its maximum force is around 25N, so it would fail our requirement). This also means that this robot can make use of passivity for exploration-exploitation task purposes in simple ways. For example, if one wished to have a robot hand that could manipulate an unknown object while learning about its mass and structural properties, the MBF could provide a basis for each finger. It could be used to detect textures as well (see, for example, Fig. 9(d-f)). This type of device would also work well for compliant tasks where a task reference must be tracked but with some flexibility, such as pushing a peg into a hole with the hole location and peg shape initially unknown, or for rough terrain locomotion tasks where the robot may 'trip' over an obstacle, and the motor system must compensate. In the latter case, a much more biological-type movement would be evident from the passive dynamics of the system, as opposed to a force-feedback or other non-backdrivable system, where a collision (which is essentially an instantaneous force, and thus the passive dynamics would be complex to reproduce and, by definition, impossible) would not lead to natural movements. Truly backdrivable locomotion systems will be useful for studying locomotion over rough terrain, a problem still largely unsolved. The same technology is incorporated into our Modular Robot Legs which are the topic of a future paper centering on locomotion.

The position estimates based upon the measurements of the potentiometer absolute sensors were compared against a 12-bit relative position rotary encoder. The experimental setup is shown in Fig. 6(a). The average absolute difference in measurements (see Fig. 6(b)) was less than the resolution

[9]This is with no range scaling of the input voltage. An improved resolution is possible.



(a) (b)

Fig. 6. (a) The testing setup for comparing the potentiometer-based position measurements with a relative encoder. (b) A comparison between the position measure from the joint sensor (potentiometer), and a direct measurement by a 12-bit relative position encoder show a very close comparison.

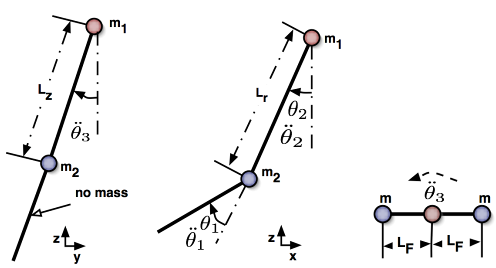
of the position measurements at 0.06 degrees.

The mass of the robot is given in Table I, which includes all electronics but not a battery (power is input from two light gauge wires during these experiments). The robot is very light (especially compared to the three-fingered Barrett hand, which weighs, with an arm adapter, 1.38kg), and for the MBF, the bulk of the mass is at the base. The heavy sections (the two small DC motors) are located far back at the center of rotation for the first degree of freedom. Additionally, the other two DOF do not couple that larger mass, and thus have very low inertial and mass properties for manipulation purposes. The MBF is made to be attached to a larger robot arm or a stationary plate, so though the base contains most of the mass, it is still a light assembly, as a complete hand with several fingers can be assembled which weighs less than one kilogram.

Since the mass and rotor inertia of the motors provide the most significant contribution to the system, inertias of each robot are determined by assuming mass-less joints and that all of the inertia is due to the motors. Thus the equations to compute inertia from known values for each joint are given by (where J_n is the inertia of joint n, $J_{m_{F_s}}$ and $J_{m_{F_B}}$ are the rotor inertias of the small and large MBF, respectively, m_{F_S} and m_{F_B} are the masses of the small MBF motor, and large MBF motor, respectively, and N_n is the gear ratio of the appropriate joint, and L_F is the length depicted in Fig. 7),

$$\begin{aligned} J_{F_3} &= J_{m_{F_S}} N_{F_3}^2, \qquad (1)\\ J_{F_2} &= J_{m_{F_S}} N_{F_2}^2, \\ J_{F_1} &= J_{m_{F_B}} N_{F_1}^2 + 2 m_{F_S} L_F^2. \end{aligned}$$

The results of the calculations are given in Table I. The inertia felt at the endpoint is very low. The robot is capable



(a) (b)

Fig. 7. Point mass approximation of the ModBot Finger used for inertia calculation. The lines (which represent the robot components) are assumed massless, as the motor inertias and masses completely dominate the system.

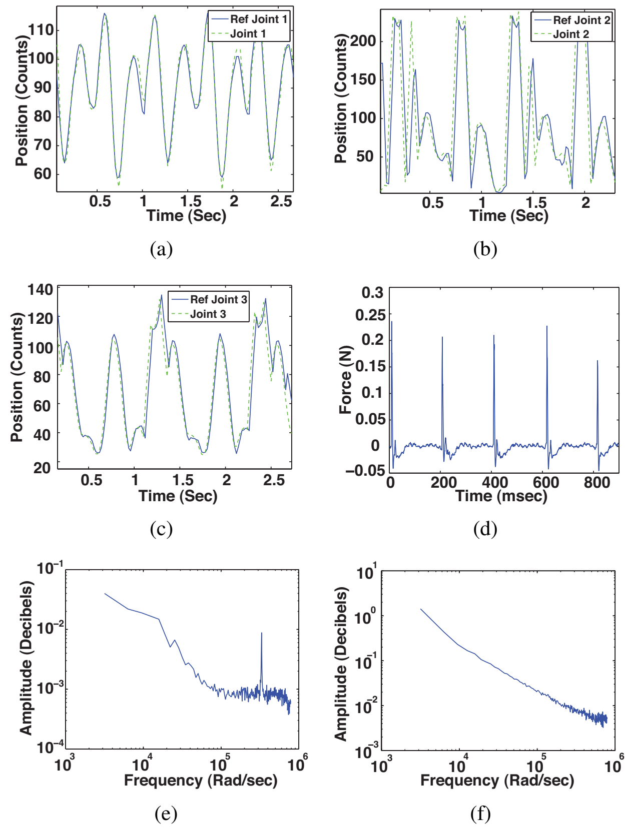


Fig. 8. (a), (b), (c) display joint angles of the MBF repeating a human movement. The trajectory is tracked with the MBF using PID control, along with integral anti-windup compensation (Each plot is one of the joint angles recorded). The trajectory is generated by a human operator backdriving the robot while the trajectory is recorded, then the human movements are used as a reference. Rapid non-smooth movements can be repeated with the robot, even with a non-model-based control design such as a PID. (d) Time domain measurements of the robot force sensor measuring tapping of the MBF tip lightly on a rigid surface. The amplification circuitry integrates a programmable gain, thus the MBF can 'focus' on manipulating a light object, as well as sense power grasps and higher forces by reducing the sensor gain. (e) Frequency components of the robot dragging its finger tip over a hard fairly smooth table surface at a constant velocity. Note the resonance frequency above 10^5Rad/sec. (f) is the same representation of frequency components but for dragging over a closed loop carpet. Note that in this case the frequency components are quite different, lacking the resonance point of the hard surface, and possessing a different 'characteristic' shape - this would facilitate automatic detection of surface types by texture.

of tracking rapid hand movements, as depicted in Fig. 8(a-c), even with a local Proportional-Integral-Derivative (PID) control algorithm for feedback. The tracking performance will improve in the future with more advanced control. Here behaviors are recorded and played back. Subtle gestures and details are captured, and can be reproduced with good repeatability. There are many commercial robot hands, and some research prototypes. The robot developed here is faster than the Barrett hand and Shadow hand (MBF - 0.02 Sec open to close vs. 1.0 and 0.2 Sec, respectively). It is also lighter (5xMBF - 0.5kg, 5xMBL - 1.2kg vs. 1.38kg and 3.9kg, respectively). It has a higher control loop maximum bandwidth (>40kHz for both vs. no report - but slow actuation and 180Hz, and higher than the ACT hand, which is approximately 250Hz). The resolution is comparable to those devices which report resolution (though resolution is adjustable by scaling the analog input range - the worst case resolution of the ModBot is slightly less than the Barrett hand at 0.08 deg vs. 0.008 deg, but higher than the Shadow hand - 0.2 deg). The Barrett hand uses relative encoders, however, whereas the ModBot uses absolute measurement. Of all the hands, the control scheme of the ModBot is the most flexible, with no required PID control. The only robots of this group which are modular in a low level sense is the ModBot. Finally, the Barrett hand and ModBot are considered most robust. The Shadow hand uses air muscles, which have benefits, but tend to burst after some time. Mechanically the structure is robust, however. The ACT hand tends to be very difficult to work on owing to its complexity, and requires specialists to create the tendon structures. The tendon cables do fail periodically, and, overall, the system would likely not survive a short drop, so robustness is evaluated as low.

Overall, the ModBot compares favorably with established devices, especially from the standpoint of control and robustness. It can provide a good platform for testing/developing algorithms that may cause other devices to self-destruct. An unstable algorithm was purposefully created and run for ten minutes on several of the ModBots to attempt to break them, and no ill effects were observed. This was after full speed collisions with joint limits and 'unsmooth' trajectories.

IV. Conclusion

We have developed a unique modular robot design methodology suitable for locomotion, manipulation, and virtual reality experiments. A new robot presented possesses the exceptional integration of features necessary for a bio-mimetic system such as backdrivability in the actuation system, minimal mass, inertia, and friction, modularity, an autonomous design, compact electronics, high bandwidth closed loop system, robust, force sensing, position sensing, capable of running advanced high performance control algorithms, capable of dynamic force production, multiple communication options and configurations. Thus they are highly compliant and have excellent passive dynamics. The aluminum skeletal frame is very rugged, as are the joints. Modularity built into the design creates a system which can be adapted quickly to many types of experiments. New devices must often be developed in science for each experiment, which is a time-consuming process. Great accomplishments have been achieved by the modularity available in many newer software systems such as LabView and Matlab. Indeed these tools have shortened development time for countless experiments. In the past, new hardware had to be developed for nearly every type of experiment. This designs supports and extends that philosophy to wireless systems and robotic hardware. It is our hope that these tools will be useful for the variety of experiments that are being performed to study human sensorimotor control as well as learning.

The results support that this robot meets its design specifications. The potentiometer sensors yield highly precise position feedback. The modular system functions well - only a source of power is required. The system has very high bandwidth and behaves well dynamically. The force production capabilities are excellent, and we have yet to break any components during testing. A high speed local PID feedback loop with an external (wirelessly communicated) reference from a PC which was used in most of the testing was very effective. It is also trivial to run the control externally from the PC, sending only motor current or voltage commands while running some more advanced model predictive control. This is the next step in controlling these robots. We have identified and continue to refine dynamic models of the system (the topic of another paper), and will integrate this information with the new simulation engine being completed in our lab for the model predictive control scheme.

Developing a robot which possesses bio-mimetic characteristics is important for many fields such as studying human sensorimotor control, artificial limbs, rehabilitation, and creating robots for interaction with humans in general contexts. Therefore the methods and issues collected and addressed in this paper are a step toward resolving these important problems.

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