Integrated Mechatronic Design for a New Generation of Robotic Hands

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Abstract: In this paper, an overall description of the design of a robotic hand is discussed, with particular attention to the required sensory subsystem, its integration within the mechanical structure of the hand and the required control architecture. Different solutions for the joint configuration and the structure of the tendon network adopted for the transmission system are present together with three types of sensors applied on the finger and on the actuators. The integrated design of the hand finger and the sensors is reported and the motivations leading to this particular implementation are thoroughly addressed, taking into account both the mechanical constraints and the control requirements.

Keywords: Robotic hands, Robotic design, Sensor systems, Sensors integration, Robot control.

1. INTRODUCTION

Researchers involved in the development of dexterous robotic hands agree that a mechatronic approach to hand design is the only way to generate new levels of functional capabilities. As reported by several authors (e.g. Lin et al. (2008)), the problems relative to the single component or subsystem design must be solved within a general frame of compatibility and integrability.

Numerous projects developed in the past could be cited. Such projects were either focused on partial approaches or, in the case they tried a complete integration between structural, sensory and control issues, not always fully successful. Comparing the features exhibited by each design with those of the reference model, the human hand, it is evident that many evolution steps are still necessary and further effort on dexterous hands development is fully motivated.

In our opinion, this effort must be oriented by explicit “driving issues” that can globally define the direction of the research. In the specific case of robot hands there are many reasons to consider a biologically inspired design a valid target to be pursued. Though the integral implementation of such a target is made difficult by inadequate knowledge and by lack of technology, this is not a reason for by-passing the problems adopting solutions that are easily available but not coherent with the chosen research direction.

A simple case to explain this point. It is well known that using pulleys to route tendons can greatly reduce problems in tendon-driven actuation of joints. Still, developing a hand based on pulley routing does not contribute to investigate and approach the structure or the efficiency of a biological tendon system, even if it is a valid short-track that allows to obtain an efficiently moving structure with limited effort.

Along with the development of our previous U.B. Hand III project and the observation of the past and current research and developments, (Kaneko et al., 1990; Butterfass et al., 2001; Kawasaki et al., 2002; Birglen and Gosselin, 2003; Jung et al., 2007), a firm belief was growing that hand design approaches not coherent with a clear driving issue risk to result fruitless: they may generate nice devices, but most of the times do not contribute to a real evolution of the state of the art.

In this paper we will present the main design aspects and work in progress related to the development of a “new generation” of robotic hands that will comply with the following driving issues:

- To present a biologically-inspired endoskeletal structure, where a fundamental role is played by external thick compliant layers. The internal articulated structure will test the applicability of non conventional joints, exploring the feasibility of alternative joint design;
- To present an actuation system made by remotely located actuators and tendon-based transmissions routed by sliding paths. Efforts will be oriented in improving a) technology, b) morphological design and c) control strategies;
- To present an appropriate sensory apparatus, exploring non-conventional and innovative solutions that provide: a) limited invasiveness in the final hand design and b) no limitations in the possible design solution of the mechanical joint.

This paper does not describe definitive solutions, but rather proposals and work in progress coherent with the adopted design issue, developed with available technology or focused on technological development, in a general frame of reciprocal compatibility. The goal is not to provide full details on each proposed component or subsystem, but simply to outline how they can globally answer to the general goals of hand design. Further details about the past and current work in the development of the U.B. Hand III can be found in Biagiotti et al. (2004); Natale and Pirozzi (2008); Berselli and Vassura (2009); Palli et al. (2009).

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2. FINGER STRUCTURE

2.1 Joint Design

Currently the finger structure (Fig. 1) is manufactured through 3D printing (rapid prototyping). This technique allows fast development and implementation of design alternatives with high morphological complexity. The main goal is to search for the maximum achievable integration between the finger components in the perspective of a reduction of the assembly complexity. Nevertheless rapid prototyping is rather poor in terms of available materials and, therefore, few different plastics can be used. Plastics that have been tested for the production of the finger structure include Fullcure®720 (E = 2870 MPa, ν = 0.33) and DurusWhite FullCure®430 (E = 1250 MPa, ν = 0.33). The design solutions which are under exploration are reported in Fig. 2 and comprise:

- Fingers with fully integral compliant joints made of the same material of the phalanx structure (DurusWhite FullCure®430), Fig. 2(a). The assembly complexity is reduced to a minimum because the finger can be obtained in one-piece only. This solution is preferred but is still unsatisfactory in terms of reliability and further investigation is needed;
- Fingers with compliant joints made with close-wound steel springs integrated in a finger structure made with plastic material (Fullcure®720), Fig. 2(b). This solution shows very good reliability but needs the integration of separate metallic components thus increasing manufacturing and assembly complexity;
- Fingers with pin joints integrated into the phalanx body (Fullcure®720), Fig. 2(c). In spite of the sliding contacts, this solution shows very good reliability: no failures occurred after about one hundred thousand working cycles. Moreover, as it happens for the fully integral compliant joints, the assembly complexity is reduced to a minimum.

Fingers with integrated pin joints is currently the adopted solution. Further research are in progress in the attempt to find geometries and design trade-off between material stiffness and yield strength that would allow the use of reliable fully integral compliant joints.

In any case, a mandatory issue is that the finger is covered by a soft layer, reproducing the role of human hand soft tissues, as depicted in Fig. 1. The latest development consider the possibility to adopt differentiated layers design for the inner structure of the soft pads, that is the adoption of a single elastic material, dividing the overall thickness of the pad into layers with different structural design (e.g. a continuous skin layer coupled with an internal layer with voids) (Berselli and Vassura, 2009).

2.2 Tendon Configuration

Actuators will be located in the forearm whereas the actuation tendons are routed through a series of sliding paths which are obtained directly within the finger structure. The selected tendon material is a multi-filament yarn made of Ultra High Modulus PolyEthylene (UHMPE). The capability of this commercially available polymer (Dynema® Fast-Flight) to accomplish a minimum of 100000 working cycles under different load conditions has been tested. The chosen tendon configuration complies the following requisites:

- To design a tendon network that satisfies the force-closure condition (Murray et al., 1994);
- To reduce the number of tendons (and therefore actuators to be placed in the forearm) in order to simplify both the mechanical structure and the control.
3. THE SENSORY APPARATUS

In this section, different types of sensors used to collect information needed by the finger controller during the system motion are presented. Even though one of the objectives of the DEXMART\(^1\) project is the development of a tactile sensor to be integrated within the fingertips of the robotic hand, these sensors are not introduced here, because different tactile sensor concepts, mainly based on optoelectronic technology, are still under investigation and the detailed design of the final solution will be carried out after the comparison among all these concepts.

3.1 Optical Angular Sensors

It is well-known that indirect measurement of joint angle through the motor angular displacement via standard rotary sensors can severely limit the performance of the whole robotic system due to the nonlinearity introduced by the transmission system and its elasticity. Therefore, the angular sensor has been designed to directly measure the joint angle. The angular sensor prototype has been tested on a finger of the U.B. Hand III, as it can be seen in Fig. 4, whose joints, constituted by elastic hinges, have a kinematic behavior that can be modeled with good approximation as an ideal 1-DOF revolute joint, with a fixed rotational center in the whole angular range (about \([0^\circ, 90^\circ]\)) (Lotti et al., 2005). As a consequence, it is possible to introduce a simplified geometrical model of two adjacent phalanges, as illustrated in Fig. 5(b), and define the joint angle \(\alpha\). The rotational center of the joint is set at the origin \(O\) of a Cartesian coordinate system, in which \(xOz\) constitutes the plane of rotation of the phalanges. Fig. 5(a) shows a single joint of a finger of the U.B. Hand III in the rest position. A LED and a photodetector are placed respectively on the first and second phalanx attached to the joint, facing each other with mechanical axes overlapping.

Since the electrical admittance of the photodetector is proportional to the incident radiation, the combined effects of the increasing distance and changing of the relative orientation between the light emitter (the LED) and the receiver (the photodetector) due to the joint bending result in a decreasing photocurrent converted into a voltage by the conditioning electronics. In particular, recalling the theory on LED radiation patterns (Kasap, 2001), an experimental model of the optical measurement system has been defined in order to select the optimal positioning of the components that guarantees the best sensitivity for the sensor over the desired angular range.

The devices used for experimental implementation are branded Avago Technologies Inc. and are spectrally matched with an infrared peak wavelength of 875 nm. Such a choice in terms of wavelength range guarantees a sufficient robustness against ambient light. These components have been mounted to the U.B. Hand III joint according to the optimal position computed from the experimental model of the system, i.e. \(p_{x0} = 2.5\,\text{mm}\) and

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\(^1\) EC FP7 IP DEXMART - DEXterous and autonomous dual-arm/hand robotic manipulation with sMART sensory-motor skills: A bridge from natural to artificial cognition.
3.2 Optical Tension Sensors

This sensor is designed for measuring the force applied by the actuator to the tendon, in order to, along with the position information retrieved by the motor encoder, implement the low level control algorithm that rejects the motor dynamics and stiction. Because of the proximity to the actuators (electric motors), conventional solutions based on strain gauges have been ruled out. A solution based on the Fiber Bragg Grating (FBG), bonded directly to the tendon, has been adopted because of the immunity to electromagnetic disturbances typical of optical fibers. The tension sensor has been designed and calibrated using a test-bench constituted by a steel tendon with a diameter of 420 µm connected, at one end, to a DC motor through a pulley via a gear train and to a load cell used to calibrate the tension sensor, at the other end. Before bonding the FBG to the steel tendon, the portion of fiber jacket corresponding to the grating position was removed, so as to avoid strain transfer loss from tendon to FBG. A picture reporting a detail of the optical sensor is presented in Fig. 7(a), where it is evident how minimally invasive is the sensing element. The strain measurement has been carried out by employing a narrow-band demodulation scheme (Zhao and Liao, 2004).

When the motor exerts a torque to the pulley, a force causes a strain variation of the tendon proportional to the stiffness of the material used to realize the tendon. Using a FBG (Kersey et al., 1997), it is possible to measure this strain and consequently the tension after a proper calibration procedure. The force $f$ is related to the output voltage $v_B$ obtained from the optical sensor signal after the demodulation and a suitable electronic conditioning as

$$f = k_B v_B$$

where $k_s$ is the tendon stiffness sketched as a lumped spring in Fig. 7(b), being $k_B$ the overall sensor sensitivity. During the calibration of the sensor, the force applied to the tendon, shown as $f$ in Fig. 7(b), has been measured using a load cell and the corresponding output voltage $v_B$ of the conditioning electronic circuit has been evaluated. The measurements have been fitted with a linear curve, whose parameters have been estimated with a least mean square technique. Fig. 8 shows the results of the sensor calibration reporting the experimental data and the fitting curve, whose equation is

$$f = 4.5v_B + 0.19$$

The sensor has been experimentally tested within a compliance control system and the results, reported in (Natale and Pirozzi, 2008), show that the sensor signal is suitable for control purposes.

3.3 Strain-gauge Tension Sensors

As explained in Sec. 4, in order to properly command the forces exerted by the tendons to the finger phalanges an
algorithm that needs as input also the tendon forces on the joint side has been employed.

The force sensors situated on the joint side are conventional strain-gauge tension sensors which have been purposely designed and manufactured to be integrated within the finger. The conservative choice to keep using strain gauges at the joint side is motivated by the need of a reliable technology that would be able to provide good performance in every grasping situation. In fact, the optical tension sensors used at motor side are sensitive to variation of curvature radius when bent. At present, this issue cannot be overcome on the joint side as easily as it is solved on the actuator side, where the sensors are kept on a safe environment and the tendons remain in a nearly straight configuration at all times.

The unconventional finger structure imposes a custom design and manufacturing of miniaturized load cells. The load cells must primarily satisfy three requirements:

- Acceptable stress/strain on both the load cell and the finger structure;
- Good sensitivity;
- Modularity.

Load cells are manufactured in Ergal (Young modulus $E = 70000\, MPa$, Poisson coefficient, $\nu = 0.3$).

A good sensor sensitivity is achieved through a noticeable deformation of the cell without exceeding either the elastic structural limit of the cell or the yield strength of the phalanx material. Furthermore, modularity is certainly a goal to be met in order to minimize production time and cost.

The explored solution is mainly an evolution of a previously published design that has been employed in the U.B. Hand III. The load cells are properly constrained in the lower side of each phalanx and provides the mechanical link between the finger and the tendons. Figure 1 shows the miniaturized load cell mounted in the finger whereas Fig. 9 shows a plot of the cell deformation in the direction measured by the strain gauge, obtained with FEM software. The load cell can be modeled as simple cantilever beams. The deformation on the direction measured by the strain gauge is $1330\mu e$. Four equal load cells are placed on each finger.

4. ROBOTIC HAND CONTROL

In this section the tendon control and the finger joints force control algorithms will be briefly discussed. As hinted before, the use of tendon as medium to transmit the forces from the actuators to the joints, introduces some drawbacks; the most noticeable is the dead-zone in force transmission due to the combined effects of friction and tendon elasticity, (Palli and Melchiorri, 2006). A control strategy that already proved to overcome this issue is based on the sliding mode controller with a boundary layer proposed in Palli et al. (2009). This control law needs the force also at the far end of the tendon, where it is fastened to the finger structure; moreover, in order to know exactly which is the force actuated by the motors (and also for rejecting actuator dynamics and frictional effects), a force sensor must be inserted on the motor side, and the optical tension sensor will be used.

The control law used in Palli et al. (2009) for the compensation of the friction acting on the tendon and then for the control of the tension at the output side can be seen as a sliding-mode plus boundary layer controller:

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T_{in} = \begin{cases} 
T_s \exp[\mu_c \theta \text{sign}(e)] & , |e| \geq e_{th} \\
T_s \left[ 1 + \frac{|e|}{e_{th}} \left( \exp[\mu_c \theta \text{sign}(e)] - 1 \right) \right] & , |e| < e_{th}
\end{cases}
$$

where $T_s$ is the output tension setpoint, $T_{in}$ and $T_{out}$ are the input and the output tension of the tendon respectively, $e = T_{in} - T_{out}$ is the tracking error, $\mu_c$ is the friction coefficient used in the controller, $\theta$ is the total angle of curvature between the input and the output side of the tendon ($\pi$ in our case), $e_{th}$ is the amplitude of the boundary layer and $e_{th}\%$ is the percent of the tension setpoint used to determine the boundary layer amplitude. In the experimental validation of the control law, the value $e_{th}\% = 5\%$ has been used.

The tendon tension controller has been tested under dif-

![Fig. 8. Tension sensor calibration curve.](image)

![Fig. 9. Load cell deformation field.](image)

![Fig. 10. Step response of the tendon tension controller.](image)
Fig. 11. Finger position controller in the joint space. Different conditions. In Fig. 10 the response of the controller to a setpoint step variation is reported. These plots show a fast response with limited tracking error and limited oscillations of the tension at the input side of the tendon. The reference forces for the sliding mode controller are computed by a high level controller from the desired torques at the fingers joints. The torques can be generated by desired trajectories or desired generalized forces, both in the joint and in the Cartesian space.

For sake of clarity a sketch of the implementation of a joint position control for one finger is depicted Fig. 11, where the various functional parts are highlighted along with the exchanged data.

The whole controller in Fig. 11 must be replicated for each finger, and a higher level controller, implemented on a different processing unit, must provide the joint references for each finger of a hand, according to the task to accomplish.

5. CONCLUSIONS

The choice of pursuing biologically inspired robotic hands heavily influences the selection of the transmission system and of the joint morphology. A tendon-based transmission system routed through a series of sliding paths, even if similar to the human hand structure, imposes the use of suitable control strategies which must be capable of correcting the combined effect of tendon elasticity and friction phenomena. The control strategy employed in this paper necessitates a sensorial system that must cope with the limits of weight, encumbrance and functionality of this specific application. Three sensors have been integrated within the mechanical structure of the hand (i.e. optical angular sensors, optical tension sensors and miniaturized load-cells) demonstrating how a congruent approach with the chosen driving issue of bio-inspired design can be successfully achieved.

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