HEXOSYS II – Towards realization of light mass robotics for the hand

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***Abstract*—This research presents a prototype of a direct-driven, optimized and light-mass hand exoskeleton that is designed to fit over the dorsal side of the hand, thus retaining palm free for interaction with real/virtual objects. The link lengths of the proposed Hand EXOskeleton SYStem (HEXOSYS) II have been selected based on an optimization algorithm. In an attempt to make the design human hand compatible, the actuators of HEXOSYS II have been chosen as a result of series of experiments on human hands of various sizes. The system based on an optimum under-actuated mechanism provides 3 DOF/finger. The resultant motion of the exoskeleton allows the wearer to perform flexion/abduction as well as passive abduction/adduction. Simple and under-actuated mechanisms together with compact mechanical design lead to realize a light mass robotic system. The first prototype of HEXOSYS II has been fabricated. Comprising of four fingers, which are enough to accomplish most of our daily life activities, the system weighs 600 grams.**

Keywords-Human hand mechatronics, Wearable robotics;hand exoskeleton system

I. INTRODUCTION

Thanks to revolutionary trends in multidisciplinary areas of mechatronics and computing, realistic exoskeleton devices do exist. They are devices aiming to transmit kinaesthetic feedback at the level of the finger in order to emulate the constrains imposed by grasping of virtually or remotely manipulated objects. Exoskeleton based systems combine machine power and human intelligence to enhance human operator's capabilities as well as machine intelligence. Therefore, such systems have greatly improved to acquire the performance level which has not been possible otherwise. They are always designed as an external mechanical link structure and find potential applications in various areas including haptics, Virtual Reality (VR) and rehabilitation.

As the field of haptics evolved, the application of force feedback techniques in VR has become more demanding. Haptic interfaces have proven to be extremely useful during the interaction of users within virtual environment. Exoskeleton robotic devices make use of the haptic sense to enhance the presence impression by reproducing the contact forces on the wearer hand. Thus the use of such system improves the interaction with the virtual environment and increases the dexterity of the operator with the virtual objects. Such interfaces can be classified into grounded and portable devices. Grounded devices can only simulate fixed objects because they limit the range of the operators' freedom of motion. For pseudo-natural interactions, portable haptic devices are used because they provide more flexibility in terms of operator's freedom. However they can simulate fixed forces only when employed with a grounded device.

Considering the domain of rehabilitation, therapy procedures are usually required to regain the normal hand strength and capabilities. In past, such procedures were executed manually by physiotherapists. Occasionally simple passive assistive devices have been employed to aid in rehabilitation. However technological revolution has evolved robotic hand exoskeletons that may be used in rehabilitation to improve the medical outcome.

The development of a hand exoskeleton device is a very challenging area, which has been targeted by many research professionals. A multi-phalanx hand exoskeleton consisting of four fingers that was able to exert forces on each phalanx of each finger was developed at PERCRO lab [1]. Few years later, researchers at Keio University realized a three fingers non-isomorphic device actuated by passive clutches [2]. Springer and Nicola at the University of Wisconsin have presented a 1-finger prototype utilizing a planar four-bar linkage. They analyzed the haptic effect perceived by the user [3]. A 2-finger hand exoskeleton intended for VR grasping simulation, having 3 Degree Of Freedom(DOF)/finger and 4 for the thumb has been developed by Stergiopoulos [4]. Lelieveld et al. proposed a 4 DOF portable wearable haptic interface with active and passive multi-point feedback for the index finger in master-slave configuration [5]. Another hand exoskeleton developed at PERCRO intended for haptic interaction in virtual environment has 3 DOF/finger and can exert controlled forces on the finger tips [6]. An under-actuated 2-finger hand exoskeleton has been conceived by researchers at IIT. It consists of an optimized Revolute-Revolute-Revolute (RRR) mechanism. The main optimization criteria are Global Isotropy Index (GII) and Perpendicular Impact Force (PIF) factors. The proposed system can be used for tele-operation, VR, Human-Robot-Interaction (HRI) [7].

This paper first introduces a brief overview of the proposed system in Section II. The system optimization is presented in Section III while Section IV deals with design requirements. Prototypes of HEXOSYS II are presented in Section V and finally Section VI comments on conclusion.

II. SYSTEM OVERVIEW

The design of a hand exoskeleton system poses numerous challenges in terms of proper choice of number of DOF, link lengths and type of actuators and sensors to provide the required functionality with adequate ergonomics. The desired requirements are reported in [7]. The solutions using a large number of actuators attempting to power most of the finger phalanges obviously result in bulky devices not potentially useful. Moreover the resultant devices become uncomfortable and cumbersome and are not recommended for repetitive use. Thus an under-actuated mechanism has been selected for HEXOSYS II.

HEXOSYS II is follow-up of research on hand exoskeleton robotic systems at IIT, Italy. Previously realized system (HEXOSYS I) has the capability to provide 45N force levels which is beyond any existing system can provide as per authors' knowledge [8]. Currently this system is being used for measuring finger stiffness. The expertise developed with HEXOSYS I encouraged us to conceive a new version having lighter mass and low volume. Reducing the physical dimensions of the system certainly improves ergonomics and grasping capability. Furthermore the new version has been targeted to support adjustment in hand size and to accommodate up to five fingers. Though both the versions have some features in common (e.g. direct-driven, portable, under-actuated) however they differ completely in terms of mechanisms, optimization strategies, actuation system etc.

The proposed conceptual mechanism of one finger of HEXOSYS II is shown in Figure 1. It is a three link planar under-actuated mechanism which is attached to user finger at a single point. A single actuation unit is used to power the three link exoskeleton. This unit is located at base of the proximal joint of the exoskeleton. Advantages of this type of system include the good ergonomics, low mechatronic complexity, portability and easy donning and removal.

The DH parameters of the device are presented in Table I. Based on these, (1) computes the overall transformation from end-effector to the base of exoskeleton.

TABLE I. DH PARAMETERS OF THE PROPOSED DEVICE

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	0	L_1	0	θ_2
3	0	L_2	0	θ_3

$$ {}^{0}_{3}T = \begin{bmatrix} C_{123} & -S_{123} & 0 & L_1C_1 + L_2C_{12} \\ S_{123} & C_{123} & 0 & L_1S_1 + L_2S_{12} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

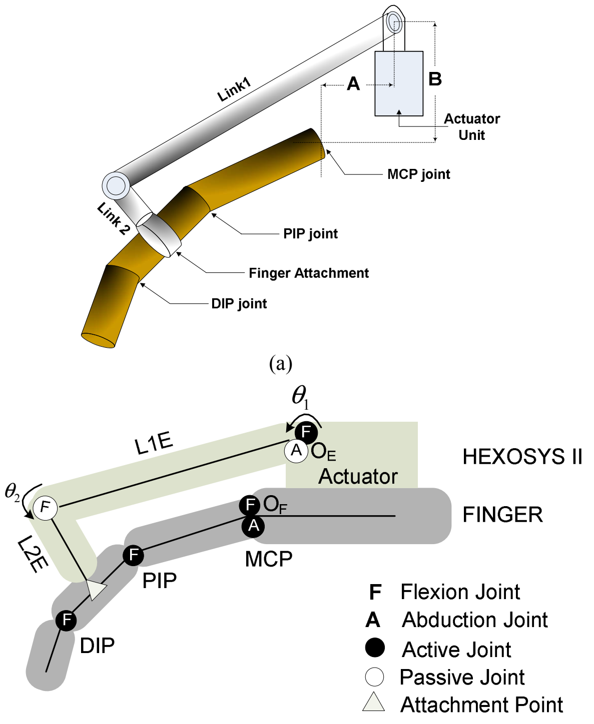
Where

$S_{123} = \sin(\theta_1 + \theta_2 + \theta_3)$
$C_{123} = cos(\theta_1 + \theta_2 + \theta_3)$

The mapping from velocities in joint space to Cartesian space (Jacobian matrix) is given by

$$ J = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 1 & 1 & 1 \end{bmatrix} \tag{2} $$

where
$a_{11} = -L_1S_1 - L_2S_{12}$
$a_{12} = -L_2S_{12}$
$a_{13} = 0$
$a_{21} = L_1C_1 + L_2C_{12}$
$a_{22} = L_2C_{12}$
$a_{23} = 0$



(a)

(b)

Fig. 1. HEXOSYS-II finger:
(a) Schematics (b) Kinematic representation

III. SYSTEM OPTIMIZATION

HEXOSYS-II link lengths have been selected as a result of an optimization algorithm. Proper choice of link lengths together with the link shape influences the kinematic performance of such robotic system. With the intention to maximize the kinematic performance, an optimization procedure prior to HEXOSYS II design has been carried out. The primary optimization criteria is kinematics, finger-exoskeleton WorkSpaces (WS) matching and worst case collision avoidance. The exoskeleton-finger attachment point has been considered for matching WS. Furthermore, the first link (L1) shown in Figure 1 has been split into three segments (L1-1, L1-2 and L1-3) as illustrated in Figure 2. This subdivision has been done to increase the collision-free reachable WS of HEXOSYS II.

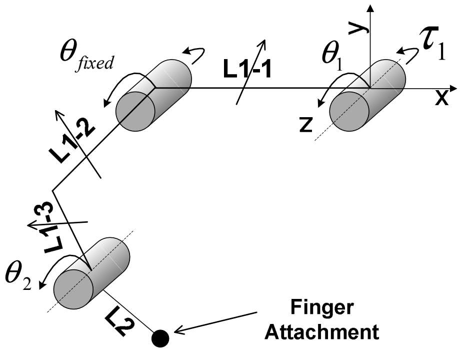


Fig. 2. Splitting the first link into three segments enhance collision-free workspace

The values of these adjustable segments are function of finger and hand size. The angle θfixed can also be varied but is fixed for a certain hand size. Hand size is the input to the optimization algorithm while the outputs include the optimum lengths of these segments and the angle θfixed .

The HEXOSYS II link lengths have been iterated through reasonable range. Each set of link lengths is then subjected to traverse through the complete finger WS for analysis. Using inverse kinematics, the set of link length is then analyzed to see how many points inside the finger WS, the exoskeleton can reach without collision. For collision detection, equidistant points (0.5cm apart) on the HEXOSYS links and the rectangular envelopes surrounding the finger centre of mass have been determined. An HEXOSYS link length set is considered as collision-free if all the points on the links reside outside the rectangular envelopes. Finally the collision-free WS is stored for comparison with the next iterated link lengths set. Figure 3 shows the overall optimization strategy of HEXOSYS II.

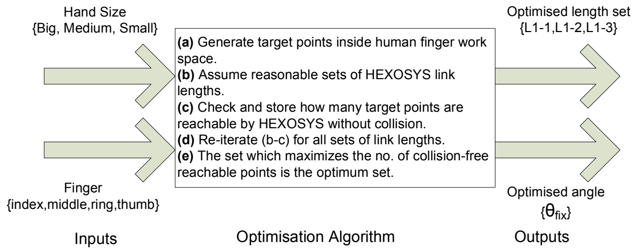


Fig. 3. HEXOSYS-II optimization algorithm

Considering index finger of a medium hand size, the maximum correlation of exoskeleton-finger WS has been found with HEXOSYS II segment lengths of L1-1=8cm, L1-2=2cm, L1-3=2cm and θ_{fixed}=55.4°. Figure 4 depicts the corresponding WS.

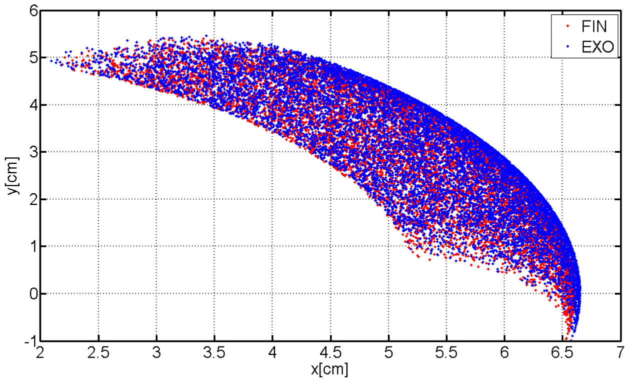
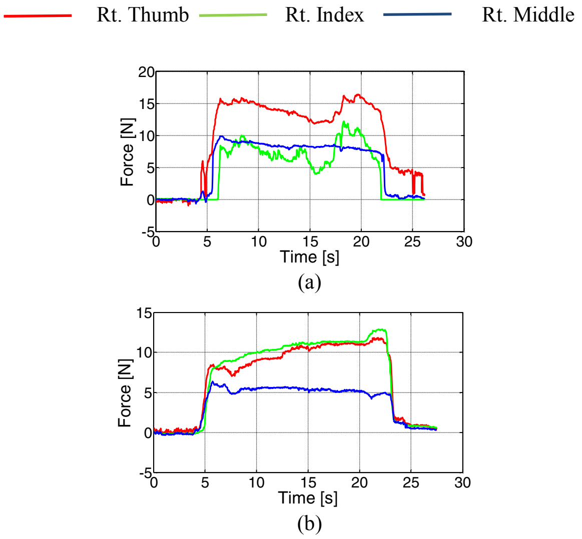


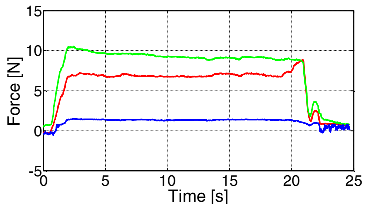
Fig. 4. HEXOSYS and finger workspaces

IV. SYSTEM DESIGN REQUIREMENTS

An analysis of the most common daily life activities of the hand has been carried to collect necessary data for the actuator selection. This analysis includes the experiments for measurement of average or maximum exerted force levels and the required range of motion. The data collected from these experiments can then be transformed to lower level actuator requirements. The experimental setup consists of a commercial data glove (from Immersion), a load cell (from ATI) and fingertip force sensors (from PPS). Using these sensors and glove, various parameters of the human hand of small, medium and big hand sizes in various activities have been collected. Figure 5 presents the force profiles corresponding to a common daily life activity i.e. interacting with a comparatively big object (ceramic cup).

The results of activities requiring average force levels demonstrate that we usually need 10N to accomplish many of our daily life activities. Another experiment intended to measure the maximum force levels exerted by human finger revealed that the maximum levels can go up to 45N. More results and further details of the conducted experiments are mentioned at [7].



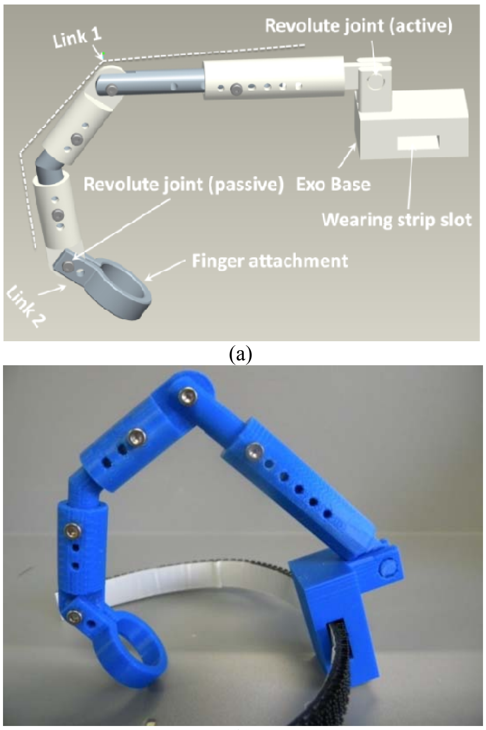


(c)

Fig. 5.Force profiles of taking a big object (cup) in case of (a) Small (b) Medium (c) Big hand sizes

V. SYSTEM PROTOTYPE

For the sake of verification of optimization results and analysis of working of the chosen mechanism, initially a simple un-actuated finger prototype has been designed using CAD tools and fabricated using a 3D rapid-prototyping printer. The prototype made up of plastic, supports passive motion of both revolute joints without imposing any unrealistic constraints. A Velcro strip has been attached with the prototype for easy donning and removal. Figure 6a and b show the CAD design and picture of the prototype respectively.

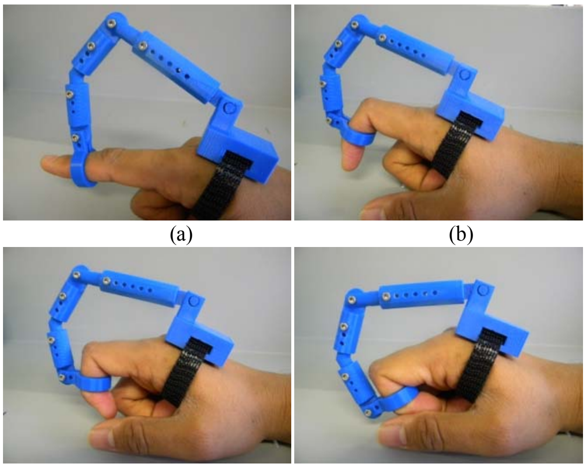


(a)

(b)

Fig. 6. The un-actuated rapid finger prototype (a) CAD design (b) Prototype

After wearing the initial prototype on the index finger, the finger has been moved from complete flexion to complete extension to observe the collision-free reachable workspace. Snapshots of a complete cycle are presented in Figure 7(a-d). As evident in the figure, the mechanism together with the optimized link lengths and shape provide full range of motion without any constraints. This validates the optimization results presented in Section III.



(a) (b)

(c) (d)

Fig. 7. Complete flexion-extension cycle showing the full collision-free workspace coverage of an index finger

The final prototype consists mainly of an actuator (Portescap 16G88-220P) with its accessories (R16 Gear and MR2 encoder) and a pair of bevel gears (1:1). The actuator having precious metal commutation is a 5W motor weighing 37gm including the gearbox. With a diameter of 16mm and overall length of 28mm, the motor can provide a stall torque of 16mNm and can move up to 5 revolutions per second. The bevel gears have been used to accommodate four fingers on the hand by changing the orientation of motor axis. The prototype incorporates position as well as force sensors to permit implementation of wide range of control strategies. Flexion, extension as well as passive abduction are supported by the prototype. The fabricated prototype of the robotic system is illustrated in Figure 8.

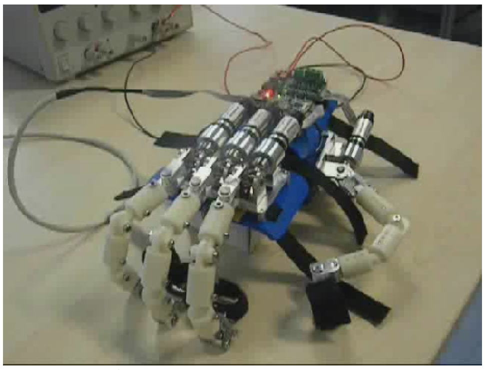


Fig. 8. HEXOSYS-II prototype

The prototype having capability to actuate thumb, index, middle and ring fingers employs symmetry in the design of all the fingers. The system provides 4 DOF per finger with only 1 active DOF. It is a wearable, portable and does not require any assistance in doning and removal. The exoskeleton provides position as well as force feedback. The resolution of force sensor is 0.01N while that of position sensor is 0.0879°. Initially, a position control system based on closed loop feedback has been implemented.

VI. CONCLUSION

We have designed and developed a hand exoskeleton robotic system. The light mass, low volume and simple mechanism of the proposed system essentially enhances the ergonomics and dexterity. The system has been emerged as a result of intensive home work, both in terms of gathering design requirements from human hand and the optimization results. The design requirements have supported the actuator selection while the optimization algorithm has paved the way to find optimum segment lengths of the robotic system. The system has been designed based on an optimum serial mechanism comprising two revolute joints. After fabrication and assembling, currently the evaluation of the proposed system is being carried out. Based on its distinguishing features, it is expected to exhibit superior performance compared to the existing systems.

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