**TAMU CLEVERarm: A Novel Exoskeleton for Rehabilitation of Upper Limb Impairments**

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*Abstract—* TAMU CLEVERarm (Compact, Low-weight, Ergonomic, Virtual/Augmented Reality Enhanced Rehabilitation arm) is a novel exoskeleton with eight degrees of freedom supporting the motion of shoulder girdle, glenohumeral joint, elbow and wrist. Of the exoskeleton’s eight degrees of freedom (DOF), six are active and the two degrees of freedom supporting the motion of wrist are passive. This paper outlines the kinematic structure of CLEVERarm, and the novel features of its design. Moreover, the control architecture is briefly introduced and some initial results are reported.

**I. INTRODUCTION**

Stroke affects an increasing portion of the aging population of world, leaving many of the survivors with different levels and forms of disability. There is a recent surge in use of robotic systems for rehabilitation purposes due to their inherent capabilities in producing high intensity, repeatable, and precisely controllable motions [1]. End-effector based systems [2] and exoskeletons [3] are the two category of the robotic systems designed to provide automated therapy to stroke patients.

End-effector based systems are structurally simpler, however, they are not capable of producing controlled motion in all joints of the upper-limb like exoskeletons. On the other, design of low-weight and compact exoskeletons that are back-drivable for maximizing the engagement of patients has proven to be challenging. Over the past couple of years, several exoskeleton systems have been designed to achieve the aforementioned goals.

TAMU CLEVERarm is a novel exoskeleton designed to achieve compactness and reduction of weight. The ultimate goal in development of the exoskeleton and its control system is functional recovery of stroke patient. This paper briefly outlines the kinematic structure of CLEVERarm, the embodiment of the design and the control architecture.

**II. TAMU CLEVERARM**

CLEVERarm has eight degrees of freedom (six active and two passive) supporting the motion of shoulder girdle, GH joint, elbow, and wrist. The motion of the GH joint and the inner shoulder are supported by five degrees of freedom. Three revolute joints, constituting a spherical linkage, is used to provide the three DoF required for the motion of GH joint. CLEVERarm uses two active degrees of freedom (a revolute joint followed by a prismatic joint) to model the displacement of GH joint center in the frontal plane of human body which allows accurate tracking of GH joint center path on the frontal plane without approximating it as a circular path [4]. Additionally, an active degree of freedom is used for assisting flexion/extension of the elbow, while pronation/supination and flexion/extension of the wrist are supported by passive degrees of freedom. The device is also equipped with visual technologies such as virtual and augmented reality to enable diverse, task-specific and immersive training scenarios. Fig. 1 shows the actual prototype, and the CAD model of the exoskeleton.

Denavit-Hartenberg (DH) convention was used for kinematic modeling of the system. Fig. 2 shows the assignment of coordinate systems and the corresponding DH parameters where \( p_1 \) through \( p_6 \) are the physical parameters of system. While \( p_1 \) and \( p_2 \) are constants, other parameters can be changed to accommodate different patient body dimensions.

**III. PROTOTYPE DESIGN AND FABRICATION**

Weight reduction and compactness of the device were the two criteria in choosing components for motorization of the design. Electric motors coupled with strain wave gears...
Harmonic Drive LLC), were used in rotary joints while the prismatic joint in the design of exoskeleton was realized by a direct drive linear actuator. To ensure reliability of joint level feedback, an incremental and an absolute encoder were used in each joint. Moreover, the two physical interfaces between the device and body were equipped with 6 axis force/torque sensors.

To minimize the weight of the device, various choices of material and manufacturing techniques were studied and a combination of Aluminum and 3D printed Continuous Filament Fabrication (CFF) Carbon Fiber reinforced plastic was selected. While carbon fiber possesses many advantageous properties, 3D printed CFF structures suffer from orthotropic strength deficiencies whereby inter-carbon fiber filament layers possess only the strength of the plastic combining them. To address this issue, structures were optimized using finite element analysis (FEA) for minimum deflection. Fig. 3.a shows a link under worst-case static loading and Fig. 3.b shows the layout of carbon fiber filament used in one of the 3D printed layers where each continuous blue line represents one continuous carbon fiber filament.

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Game environments are part of the control architecture of the CLEVERarm since they represent the desired position for the patient hand. As Fig. 4 shows, desired positions from the game environment are fed into the reference generation block within the control architecture to generate human-like motions considering the scapulothoracic rhythms using the algorithms developed by the authors [6]. Friction compensation can be achieved by developing empirical models [8]. Alternatively, admittance-based control approaches can be used to improve back-drivability by compensating the effects of friction [7]. Fig. 5 shows two different impedance values using admittance control.

**REFERENCES**

[1] B. R. Brewer, S. K. McDowell, and L. C. Worthen-Chaudhari, "Poststroke upper extremity rehabilitation: a review of robotic systems and clinical results," *Topics in stroke rehab*, pp. 22-44, 2014.

[2] H. I. Krebs, S. P. Buerger, K. A. Jugenheimer, D. Williams, and N. Hogan, "3-D extension for MIT-MANUS: a robot-aided neuro-rehabilitation workstation," in ASME IDETC/CIE, DETC2000/MECH-14151, Baltimore, MD, 2000.

[3] T. Nef, M. Guidali, and R. Rienz, "ARMin III-arm therapy exoskeleton with an ergonomic shoulder actuation," *Applied Bionics and Biomechanics*, vol. 6, pp. 127-142, 2009.

[4] A. Zeiaee, R. Soltani-zarrin, R. Langari, and R. Tafreshi, "Design and kinematic analysis of a novel upper limb exoskeleton for rehabilitation of stroke patients," in IEEE/RAS-EMBS International Conference on Rehabilitation Robotics, London, pp. 759-764, 2017.

[5] M. W. Spong, S. Hutchinson, M. Vidyasagar, *Robot modeling and control*, Vol. 3. New York: Wiley, 2006.

[6] R. Soltani-Zarrin, A. Zeiaee, R. Langari, and N. Robson, "Reference path generation for upper-arm exoskeletons considering scapulothoracic rhythms," in in IEEE/RAS-EMBS International Conference on Rehabilitation Robotics, London, pp. 753-758, 2017.

[7] C. Carignan, J. Tang, S. Roderick. "A configuration-space approach to controlling a rehabilitation arm exoskeleton", IEEE 10th International Conference on Rehabilitation Robotics, pp. 179-187, 2007.

[8] T. Nef, P. Lum. "Improving backdrivability in geared rehabilitation robots." *Medical & biological engineering & computing*, vol. 47, pp. 441-447, 2009.