Dynamic analysis and control of a Hybrid serial/Cable driven robot for lower-limb rehabilitation

M. Ismail[1] , S. Lahouar[2] and L. Romdhane[1,3]

[1] *Mechanical Laboratory of Sousse (LMS), National Engineering School of Sousse, University of Sousse, Sousse 4000, Tunisia, e-mail:mourad.smail@gmail.com , lotfi.romdhane@gmail.com*

[2] *Laboratoire de Génie Mécanique (LGM), National Engineering School of Monastir, University of Monastir, Monastir 5019, Tunisia, e-mail:samirlahouar@gmail.com*

[3]*Mechanical Engineering Department, American University of Sharjah, PO Box 26666, Sharjah, United Arab Emirates, e-mail: lromdhane@aus.edu*

Abstract. In this work, we propose the use of a hybrid serial/cable driven robot for lower limb rehabilitation of disabled patients. The robot consists of an exoskeleton actuated via cables. A strategies to calculate and keep the values of the tensions in the cables positive during the motion is investigated. We show that the Null Space method yields good results and is less demanding in computational time; hence it is a good choice for real-time implementations. The human walking were simulated to show the effectiveness of the proposed method. The simulation results show that the values of the tensions in the cables can be maintained positive during the motion. The presented work shows that this hybrid parallel-serial cable robot could be used for rehabilitation of the lower limb.

Key words: Rehabilitation robot Hybrid serial/cable robot Positive tensioning Dynamic modeling.Stiffness

1 Introduction

Robotic Rehabilitation is getting more and more popular during the last few years[1]. This increase is mainly due to its relative effectiveness, in general [2],[3],[4], and in medical applications [5], in particular. Rehabilitation is used to recover from any movement disorder and mainly as a movement therapy for stroke and spinal cord injury. According to [6],[7] strokes are the second cause of disability,15 million people worldwide suffer a stroke every year. Almost, six million died and another five million are left permanently disabled. Rehabilitation can be the best and maybe the only way to regain movement for these patients.

Robotic rehabilitation can be seen as a robot-assisted medical rehabilitation, where the robot is not meant to replace the handicapped member, but rather assist the patient to boost his autonomy. [8].

The emergence of robotic therapy as treatment for both upper and lower extremities has revealed a numerous challenges like modeling [9] of both the exoskeleton and the limb, dynamic identification [10],[7], controller design [11],[12] and adaptive control [7], sensing and measurement [13],. Two different devices have been studied in the literature. The first one is an exoskeleton, where the extremity of the patient is actively driven by the robot. This type of devices is mainly used for patients that cannot recover their autonomy. The second device is robotic rehabilitation, where the patient is trained by the robot, in order to improve the strength of his extremity. The final objective is to have the patient recover his autonomy after a certain number of training sessions.

Actuation is also a challenging problem. Rather than using electric motors, in [14] the authors suggested the use of a pneumatically actuated prosthesis which helps to reduce the cost and provides a higher power-to-weight ratio. In this work, we consider solving the problem of lower limbs rehabilitation by the means of a hybrid serial/cable robot, which benefits from both the stiffness of serial manipulators and the higher power-to-weight ratio of cable robots, making it a good candidate for rehabilitation applications. As joints are not directly actuated, the use of cables reduces greatly the cost and the complexity of the mechanical construction. On the other hand, the unidirectional nature of the force that can be applied by cables suggests the use of a specific control scheme to keep a positive tension in the cables. The problem becomes more challenging when a given dynamic response of the exoskeleton is needed.

The used robot [15],[16] consists of an exoskeleton actuated via cables. First, we start by studying the control problem of a special case where cables are attached to the feet, then we generalize the study to all possible attachment points between the fixed frame and the mechanical passive serial support.

2 Modeling

The exoskeleton proposed in this work can be thought of as a hybrid serial/cable robot (See Fig. 1). Because a total control over the lower limbs is needed, a planar, fully constrained and fully actuated robot is used. It has three degrees of freedom, and it moves in a vertical plane. The robot includes a serial support composed of three links and three passive joints. The actuation is provided by the mean of 4 cables attached to the exoskeleton and windings around four pulleys which are actuated using four motors. The three links undergo the effects of gravity, which are the only external forces applied to the system, along with the four torques of the actuators. The geometric parameters of the system are defined in Fig. 1.

Hybrid serial/cable robot is a combination of a serial passive arm actuated via cables. A full study of the kinematics of the cable robot can be found in [15].

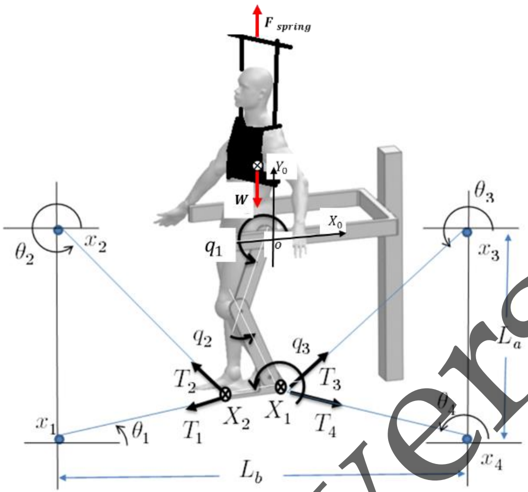


Fig. 1 Hybrid parallel/serial rehabilitation robot

The upper body weight is considered to be completely compensated by the force applied by the spring since the patient legs are tightly attached to the exoskeleton which is fixed in the center O of the reference frame R_0.

One can express the dynamics of the system according the Lagrange formulation:

$$\frac{\mathbf{d}}{\mathbf{dt}}\left(\frac{\mathbf{dL}}{\mathbf{d\,\dot{q}}}\right) - \frac{\mathbf{dL}}{\mathbf{dq}} = \boldsymbol{\tau} - \mathbf{C}\,\dot{\mathbf{q}} \tag{1}$$

$$\mathbf{M}(\mathbf{q})\,\ddot{\mathbf{q}} + \mathbf{n}\,(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{p}\,(\mathbf{q}) = \boldsymbol{\tau} - \mathbf{C}\,\dot{\mathbf{q}} \tag{2}$$

$\boldsymbol{\tau} = [\tau_1\ \tau_2\ \tau_2]^T$, Where $\boldsymbol{\tau}$ the generalized torque applied to the robot joint. $\mathbf{c}_i$ is the viscos friction of the exoskeleton joints q_i.

The 3x3 matrix $\mathbf{M}(\mathbf{q})$ is the mass matrix, the 3x1 vector $\mathbf{n}\,(\mathbf{q},\dot{\mathbf{q}})$ is the centrifugal and Coriolis forces vector and the 3x1 vector $\mathbf{p}\,(\mathbf{q})$ is the gravity force vector.

The tension exerted by cables 1 and 2 is $\mathbf{T_{12}} = [\mathrm{T}_1 \quad \mathrm{T}_2]^\mathrm{T}$ in the same way $\mathbf{T_{34}} = [\mathrm{T}_3 \quad \mathrm{T}_4]^\mathrm{T}$ is the tension of cable 3 and 4. Hence, the relationship between joint torques and cable tensions can be expressed as:

$$\mathbf{J}_2(\mathbf{q})^\mathbf{T}\mathbf{S}(\theta_1,\theta_2)\mathbf{T_{12}} + \mathbf{J}_1(\mathbf{q})^\mathbf{T}\mathbf{S}(\theta_3,\theta_4)\mathbf{T_{34}} = \boldsymbol{\tau} \tag{3}$$

Where $\mathbf{S}(\theta_{ij}) = -\begin{bmatrix} \cos(\theta_i) & \cos(\theta_j) \\ \sin(\theta_i) & \sin(\theta_j) \end{bmatrix}$

The dynamics of the pulleys and the actuators cannot be neglected, however, and the following expression represents their dynamics, where j is moment of inertia and c the Coulomb friction:

$$\tau_m - I_m\ddot{\beta} - C_m\dot{\beta} = r\,T \tag{4}$$

Where $\mathbf{T} = [\mathbf{T_1} \quad \mathbf{T_2} \quad \mathbf{T_3} \quad \mathbf{T_4}]^T$and τ_m is the motor torque.

Let β_i be the pulley's angular position, one can express the system dynamics as

$$\mathbf{M}(\mathbf{q})\ (\ddot{\mathbf{q}}) + \mathbf{n}\ (\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{p}\ (\mathbf{q}) = \mathbf{J}(\mathbf{q})^T\mathbf{S}(\theta)\,\frac{(\tau_m - I_m\ddot{\beta} - C_m\dot{\beta}\ )}{r} - \mathbf{C}\ \dot{\mathbf{q}} \tag{5}$$

For more convenience we define $\mathbf{M}^*(\mathbf{q}, \theta) = \mathbf{r}\mathbf{S}^{-1}(\theta)\mathbf{J}(\mathbf{q})^{+T}\mathbf{M}(\mathbf{q})$ and $\mathbf{n}^*(\mathbf{q}, \dot{\mathbf{q}}, \theta, \beta, \dot{\beta}) = \mathbf{r}\mathbf{S}^{-1}(\theta)\mathbf{J}(\mathbf{q})^{+T}(\mathbf{n}\ (\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{p}\ (\mathbf{q}) + \mathbf{C}\,\dot{\mathbf{q}}) - I_m\,\ddot{\beta} - C_m\dot{\beta}$

We get:

$$\mathbf{M}^*(\mathbf{q}, \theta)\ \ddot{\mathbf{q}} + \mathbf{n}^*(\mathbf{q}, \dot{\mathbf{q}}, \theta, \beta, \dot{\beta}) = \tau_m \tag{6}$$

Finally we simulate the robot according to Eq. (6).

The actuator friction and inertia are taken into account according to Eq. (4). The simulation relies on the dynamics of the exoskeleton, which is defined by the mass matrix $\mathbf{M}^*$ and the force vector n^*. The solution is obtained using the ordinary deferential equation numerical solver ode23t in MATLAB.

3 Task Space Control and Positive cable tensioning

The control strategy needs to track the positions of both $\mathbf{X_1}$ and $\mathbf{X_2}$ simultaneously in the task space [17] and also be able to keep positive and bounded tensions. To track $\mathbf{X} = \begin{bmatrix} \mathbf{X_1} \\ \mathbf{X_2} \end{bmatrix}$.we use the inverse dynamics to get the desired motors torque.

$$\tau_m = \mathbf{M}^*(q, \theta)\mathbf{J}^+\ (\ddot{\mathbf{X}} - \ \dot{\mathbf{J}}\dot{\mathbf{q}}) + \mathbf{n}^*(\mathbf{q}, \dot{\mathbf{q}}, \theta, \beta, \dot{\beta}) \tag{7}$$

Where $\ddot{\mathbf{q}} = \mathbf{J}^+\ (\ddot{\mathbf{X}} - \ \dot{\mathbf{J}}\ \dot{\mathbf{q}})$.

Through a PID controller Fig. 2, the desired torques for a given motion can be calculated as follows:

$$\tau_m|_d = \mathbf{M}^*(q, \theta)\mathbf{J}^+\ (\ddot{\mathbf{X}}\mathbf{d} + K_v\delta\,\dot{\mathbf{X}} + K_p\delta\mathbf{X} + K_I\int\delta\mathbf{X} - \ \dot{\mathbf{J}}\,\dot{\mathbf{q}}) + \mathbf{n}^*(\mathbf{q}, \dot{\mathbf{q}}, \theta, \beta, \dot{\beta}) \tag{8}$$

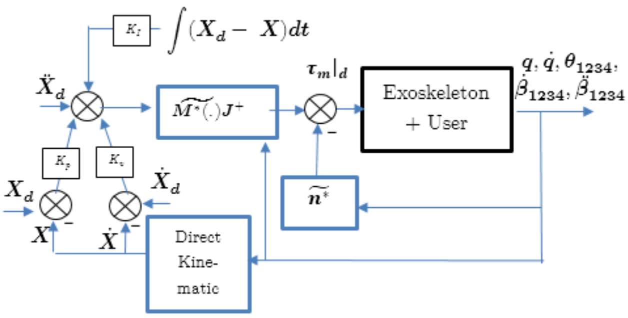


Fig. 2 Proposed controller scheme

Where $\mathbf{M^*}\widetilde{(\mathbf{q}, \theta)}$ and $\mathbf{n^*}(\mathbf{q}, \widetilde{\dot{\mathbf{q}}, \theta}, \dot{\beta}, \ddot{\beta})$ are estimation of $\mathbf{M^*}$ and $\mathbf{n^*}$ and $\tau_m|_d = [\tau_{m1} \quad \tau_{m2} \quad \tau_{m3} \quad \tau_{m4}]_d^T$ the desired torques to control X_2 by the mean of motor 1 and 2 through cable 1 and cable 2 respectively X_1 by the mean of motor 3 and 4 through cable 3 and cable 4.To track $\mathbf{X_1}$ and $\mathbf{X_2}$ simultaneously, the desired torque applied to the joints is:

$$\tau_d = \mathbf{M}(\mathbf{q})\{\mathbf{J}^+(\ddot{\mathbf{X}}_d + K_v\delta\dot{\mathbf{X}} + K_p\delta\mathbf{X} + K_I\int\delta\mathbf{X} - \dot{\mathbf{J}}\dot{\mathbf{q}})\} + \mathbf{n}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{p}(\mathbf{q}) + C\dot{\mathbf{q}} \tag{9}$$

The minimum cable tension is given by:

$$\hat{\mathbf{T}} = \dot{\mathbf{S}}^+(\theta)\mathbf{J}(\mathbf{q})^{+T}\tau_d \tag{10}$$

To optimize the cable tension, we could add $\mathbf{N}\left(\mathbf{J}(\mathbf{q})^T\dot{\mathbf{S}}(\theta)\right)\mathbf{k}$ so that $\hat{\mathbf{T}} + \mathbf{N}\left(\mathbf{J}(\mathbf{q})^T\dot{\mathbf{S}}(\theta)\right)\mathbf{k}$ becomes positive (Fig.3). Where $\mathbf{k}$ is a positive vector. And finally:

$$\tau_m = r\hat{\mathbf{T}} - (\mathbf{I}_m\ddot{\beta} + \mathbf{C}_m\dot{\beta}) \tag{11}$$

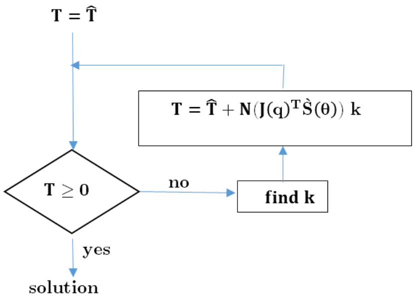


Fig. 3 Real time approach to find k

4 Simulations results.

There is an infinite number of variations to where one could attach the cables both in the exoskeleton and the fixed frame. In fact, some cable attachment point configurations will yield a better dynamic response and more importantly, will keep positive and bounded cable tensions. To avoid going through elaborated optimization strategies, we simply selected one configuration, based on some trial and error tests. This configuration is illustrated in Fig. 4.

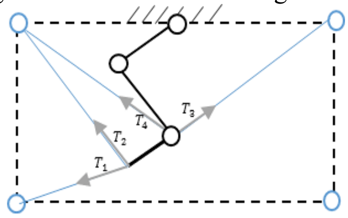
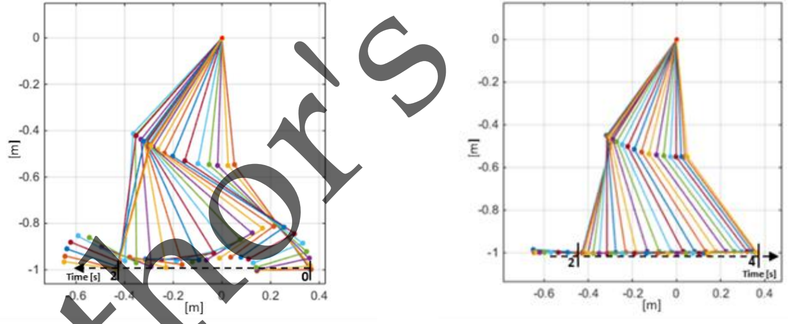


Fig. 4 Cable attachment configuration chosen for the simulations.

The two phases of a typical human walk on a treadmill are presented in Fig. 5a and 5b. In the first phase the path describing the heel and the toe movement is defined by a set of discrete points.



(a) (b)

Fig. 5 human walk (a) first phase; (b) second phase.

The second phase uses two points, the initial and final pose of the heel and toe. The trajectory is a straight line and described by a quintic polynomial profile.

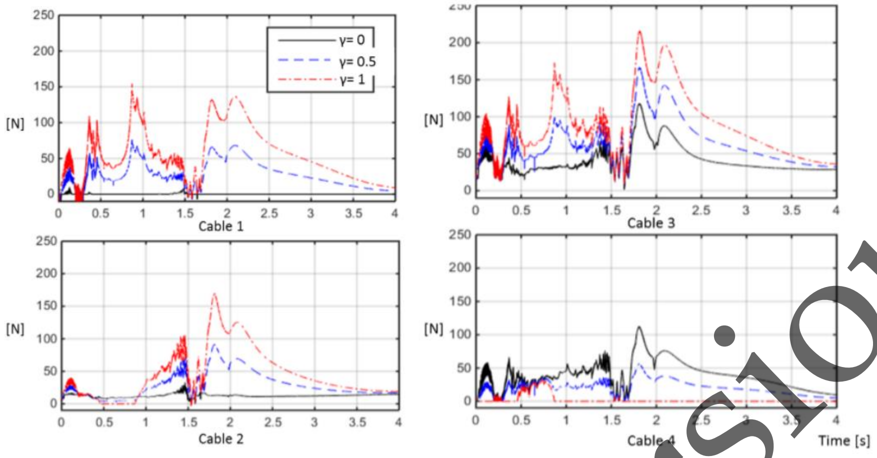


Fig. 6 Cable Tensions

Fig. 6 shows the tensions in the four cables and along the whole trajectory. We control the stiffness of the robot by varying the internal forces, which depend on in the value of γ a scalar describing the stiffness of the system.

As γ increases, tensions increase in average, except for cable 4 Fig. 6 which decreases in our case from 40 N to less than 5 N.

5 Conclusion

In this work, we demonstrated the effectiveness of using a hybrid cable-driven robot with a serial passive exoskeleton for lower limbs rehabilitation. Two control strategies, i.e., the linear programming method and the null space method, were investigated and compared. The null space method was shown to be more effective for real-time control. Two different trajectories, simulating the human walking were analyzed. The tensions in the cables were calculated and the simulations showed that it is possible to keep positive tensions in the cables, at all times. The presented work showed that this hybrid parallel-serial cable robot could be used for rehabilitation of the lower limb.

References

1. Kwee, H.H., *The Spartacus Telethesis : Soft Touch . Proc. First Intern. Conf. on Telemanipulators for the Physically Handicapped*, in *First Intern. Cof on Telemanipulators for the Physically Handicapped*. 1978: Rocquencourt, France.
2. (Ed.), F.R., *Interactive Robotic Aids -one Option for Independent Living: an International Perspective*, in *Monograph 37, World Rehab. Fund*. 1986: New York.
3. Egginton R, S.J., *Proc. First Intern. Workshop on Robotic Applications in Medical and Health Care*, in *National Research Council of Canada*. 1988: Ottawa.
4. Gilbert M, in *Intern. Conf on Rehabilitation Robotics*. 1990: duPont Institute,Wilmington, Delaware.
5. Krebs, H.I., et al., *A paradigm shift for rehabilitation robotics.* IEEE Engineering in Medicine and Biology Magazine, 2008. **27**(4): p. 61-70.
6. Mukherjee, D. and C.G. Patil, *Epidemiology and the Global Burden of Stroke.* World Neurosurgery, 2011. **76**(6): p. S85-S90.
7. Mackay, J., et al., *The atlas of heart disease and stroke*. 2004: World Health Organization.
8. Ed Rocon, J.L.P., *Exoskeletons in Rehabilitation Robotics.* 2011: Springer. 137.
9. Woo, H.S. and O. Kwon. *Combined kinematic analysis of a hybrid 7-DOF rehabilitation robot*. in *Control, Automation and Systems (ICCAS), 2012 12th International Conference on*. 2012.
10. Guo, X. and Y. Yan. *Application of dynamics parameter identification of limb for rehabilitation robot*. in *2010 3rd International Conference on Biomedical Engineering and Informatics*. 2010.
11. Ozkul, F. and D.E. Barkana. *Design of an admittance control with inner robust position control for a robot-assisted rehabilitation system RehabRoby*. in *Advanced Intelligent Mechatronics (AIM), 2011 IEEE/ASME International Conference on*. 2011.
12. Wang, H., et al. *Realization of human-computer interaction of lower limbs rehabilitation robot based on sEMG*. in *Cyber Technology in Automation, Control, and Intelligent Systems (CYBER), 2014 IEEE 4th Annual International Conference on*. 2014.
13. Zhang, F., et al. *Research on sensing and measuring system for a hand rehabilitation robot*. in *2013 IEEE International Conference on Robotics and Biomimetics (ROBIO)*. 2013.
14. Zheng, H. and X. Shen, *Design and Control of a Pneumatically Actuated Transtibial Prosthesis.* Journal of Bionic Engineering, 2015. **12**(2): p. 217-226.
15. Ismail, M., S. Lahouar, and L. Romdhane, *Collision-free and dynamically feasible trajectory of a hybrid cable–serial robot with two passive links.* Robotics and Autonomous Systems, 2016. **80**: p. 24-33.
16. Lahouar, S., et al., *Collision free path-planning for cable-driven parallel robots.* Robotics and Autonomous Systems, 2009. **57**(11): p. 1083-1093.
17. Hsu, P., J. Hauser, and S. Sastry. *Dynamic control of redundant manipulators*. in *Robotics and Automation, 1988. Proceedings., 1988 IEEE International Conference on*. 1988.