Modeling and Design of ANFIS Dynamic Sliding Mode Controller for a Knee Orthosis of Hemiplegia

Belay Eshetu - Hawassa University, Ethiopia

Introduction

The neuromuscular and musculoskeletal systems must work together for human mobility to occur naturally, and any accident, ailment, or disease will change how a person moves [1]. Pathologies that affect the neuromuscular and musculoskeletal systems have severe mobility implications. A handicap that affects only one side of the body, known as hemiplegia, is brought on by the brain's motor nerve cells being impaired. Patients with hemiplegia experience walking problems and exhaustion as a result of reduced muscle strength and mobility impairment.

The use of assistive devices to control the loss of strength and range of motion is becoming common. Knee-Ankle-foot orthoses (KAFOs) are frequently employed to help hemiplegic patients correct their gait. [2] used a spring at the patient's knee joint to generate the necessary knee extension at the end of the swing phase. Energy stored in the spring was also used to create knee flexion at the start of the swing phase.

In this article, a knee orthosis that is monitored by dynamic SMC is designed in conjunction with an AI-based technique called ANFIS, which combines the benefits of neural networks with fuzzy inference systems. Nonlinear disturbance observer (NDO) and dynamic sliding mode controller-based adaptive neuro-fuzzy inference system (ANFIS) tracking control for knee joint is developed. In unusual instances, such as a large patient jerk, spasm and undesired disturbances, nonlinear controllers are required to maintain the patient's safety.

Modelling of a knee orthosis

By considering the thigh and shank segments of the human leg as depicted in **Fig. 1**, the Euler-Lagrange technique is utilized to derive the nonlinear dynamic equation of motion for the coupled human orthosis system.

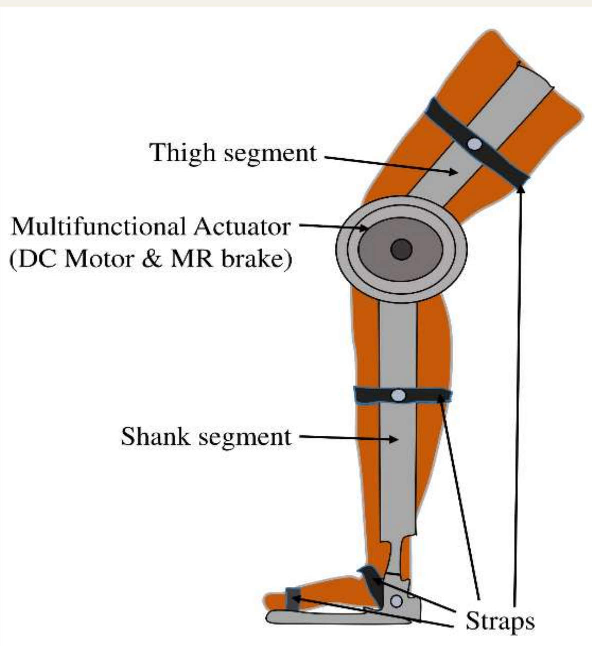

Fig. 1. Configuration of knee orthosis

A double pendulum can be used to model a human leg in the swing phase of walking on level ground as shown in **Fig. 2(A)**. A double inverted pendulum can be used to model a human leg in the stance phase of walking on level ground as shown in **Fig. 2(B)**.

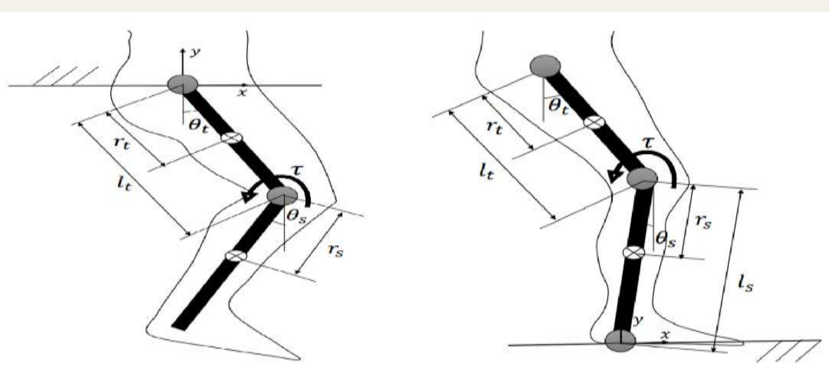

Fig. 2. Knee actuated orthosis model: (A) swing phase, (B) stance phase

Euler-Lagrange equations of motion

The dynamic equation governing the nonlinear model of human/orthosis is given as:

$$M(\theta)\ddot{\theta}+C(\theta)\,\dot{\theta}^2+G(\theta)=\zeta$$

Where θ is joint angle, $M(\theta)$ is inertial matrix, $C(\theta)$ is Coriolis-centrifugal matrix, $G(\theta)$ is gravity effects matrix and ζ is torque

The dynamic equation to focus on in swing phase is:

$$m_s l_t r_s cos(\theta_t-\theta_s)\ddot{\theta}_t+(m_s\, {r_s}^2+I_s)\ddot{\theta}_s-m_s l_t r_s sin(\theta_t-\theta_s)\,{\dot{\theta}_t}^{2}+m_s g r_s\, sin\,\theta_s+B_s\dot{\theta}_s+A_s sign\big(\dot{\theta}_s\big)=\zeta_s+\zeta_d$$

Where θ_t is thigh angle and θ_s is shank angle.

The dynamic equation for stance phase is:

$$(m_s(l_s-r_s)^2+m_t{l_s}^2+I_s)\,\ddot{\theta}_s+m_t l_s(l_t-r_t)\,cos(\theta_s-\theta_t)\,\ddot{\theta}_t+m_t l_s(l_t-r_t)sin(\theta_s-\theta_t)\,{\dot{\theta}_t}^{2}+(m_s(l_s-r_s)+m_t l_s)g sin\,\theta_s+B_s\dot{\theta}_s+A_s sign\big(\dot{\theta}_s\big)=\zeta_s+\zeta_d$$

In the equations of motion, the length and mass requirements of the wearer's limbs are constant and must be determined separately for each wearer. A man with a weight of 80 kg and a height of 1.75m was considered in this study.

ANFIS-NDO-DSM controller

Sliding mode controller (SMC) is among the most effective nonlinear resilient control techniques. The SMC is resistant in the face of system perturbation and external disturbance under specific conditions. This control technique, on the other hand, has several problems associated with substantial control chattering, which can wear coupled systems and generate unwanted high-frequency dynamics. Numerous techniques have been used in prior studies to reduce chattering. [3] suggests using a dynamic sliding mode controller (DSMC) to get the control law by integrating a function that includes the switching control term. The chattering is significantly reduced by this integration. In this work, ANFIS and DSMC are used together to address the parametric variation, disturbances caused by patient spasms, jerks, ground response effects, and unmodeled uncertainty that situated to the system adaptively. An observer for nonlinear disturbances (NDO) is first designed because the knee orthotic system has patient induced disturbances and uncertainty.

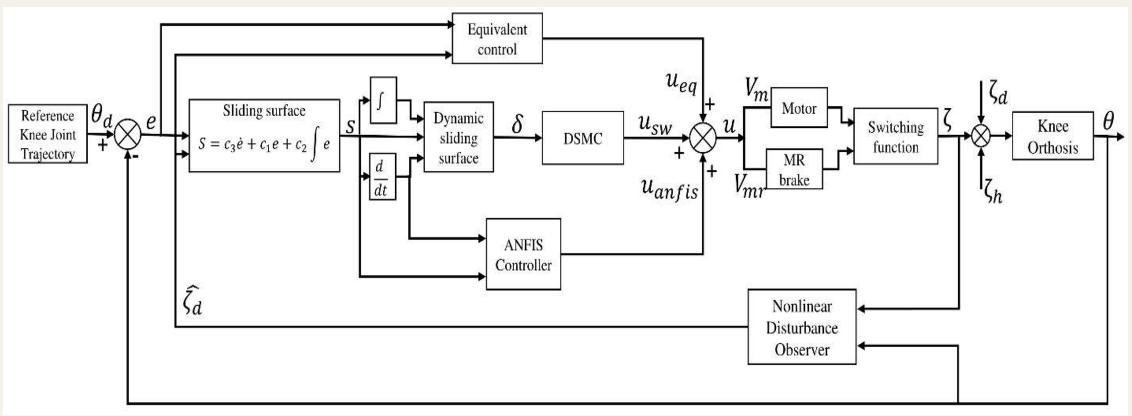

Fig. 3. Structure of the proposed ANFIS NDO dynamic sliding mode controller

The control law the dynamic sliding mode controller is designed as:

$$\dot{u}=M[c_3(\dddot{\theta}_{ds}-M^{-1}(\dot{\hat{\zeta}}_d-(\dot{C}(\theta)\,\dot{\theta}^2+\dot{G}(\theta)+\dot{F}\big(\dot{\theta}\big))))+(c_1+\lambda_1 c_3)(\ddot{\theta}_{ds}-M^{-1}(u+\hat{\zeta}_d-(C(\theta)\,\dot{\theta}^2+G(\theta)+F\big(\dot{\theta}\big))))+(c_2+\lambda_1 c_1+\lambda_2 c_3)\dot{e}+(\lambda_1 c_2+\lambda_2 c_1)e+\lambda_2 c_2\int_0^t e+\beta sign(\delta)+k\delta]$$

$$u=\int\dot{u}$$

ANFIS Design for the Knee Orthosis

ANFIS is a popular artificial intelligence that takes advantage of fuzzy logic and neural networks (FL). We can obtain good reasoning in both quality and quantity if we combine these two intelligent approaches. We have fuzzy reasoning and network calculations, in other words. It is commonly utilized in a variety of domains for complex and nonlinear systems. [4] developed the ANFIS design, which is shown in **Fig. 4** with a fixed node in the circle and an adaptable node in the square.

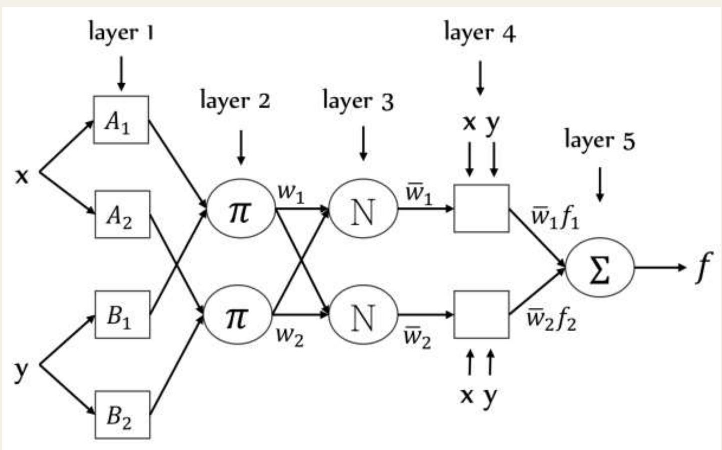

Fig. 4. ANFIS Configuration [4]

The ANFIS control approach is employed to enhance the normal knee trajectory tracking performance of knee orthosis system by addressing the parametric variation in the system. MATLAB R2021a neuro-fuzzy designer GUI is used to develop the ANFIS controller. NDO-DSMC and DSMC strategy for stance and swing phase respectively are used to create a training dataset with two inputs and one output. The two inputs utilized to create the neuro-fuzzy controller are the sliding surface (s) and derivative of the sliding surface (ds).

The nominal mass values are raised by up to 20% to account for the parametric variation/uncertainties. For data generation, switching control is retrieved for different parameter variation varying from 0% to 20% with a step size of 20% parameter variation. Total 2004 number of dataset of sliding surface (s), its derivative (ds) and switching control (u_{sw}) are collected by NDO-DSMC and DSMC. Among those dataset, 1670 dataset was used for training and 334 dataset was used for testing purpose.

$$dataset=\begin{matrix} s^T & \dot{s}^T & u_{sw@M_t=8kg\&M_s=7.38kg} \\ s^T & \dot{s}^T & u_{sw@M_t=8.32kg\&M_s=7.6752kg} \\ \vdots & \vdots & \vdots \\ s^T & \dot{s}^T & u_{sw@M_t=9.6kg\&M_s=8.856kg} \end{matrix}$$

For parameter fluctuations in the orthotic system, the ANFIS model offers adaptive switching control (u_{anfis}). The ANFIS structures are created and trained after numerous simulation runs with different MF and epoch numbers have been performed. Then, the ANFIS architecture is inputted to the coupled human-orthosis system by adding up with the NDO-DSMC.

Table 1. ANFIS training results using different MF

MF type	Training Parameters	Phase			
		Stance		Swing	
		Motor function	MR function	Motor function	MR function
trimf	MF number	10-10	10-10	10-10	10-10
	Epoch	10	10	5	5
	RMSE	**0.0003714**	**0.0001147**	0.0137231	0.0042421
trapmf	MF number	10-10	10-10	10-10	10-10
	Epoch	10	10	10	15
	RMSE	0.0005923	0.0001830	0.0095968	0.0029852
gbellmf	MF number	10-10	10-10	10-10	10-10
	Epoch	10	10	5	5
	RMSE	0.0036309	0.0011223	0.0059423	0.0018349
gaussmf	MF number	10-10	10-10	10-10	10-10
	Epoch	10	10	5	5
	RMSE	0.0031917	0.0009933	**0.0023447**	**0.0007303**
gauss2mf	MF number	10-10	10-10	10-10	10-10
	Epoch	10	10	5	5
	RMSE	0.0023855	0.0007387	0.0062425	0.0019350

Results

The hemiplegic/stroke patient is enabled to follow trajectory collected from healthy person. A normal knee joint trajectory taken from normal person is utilized as a reference, and the tracking accuracy of the reference trajectory is used to evaluate how well the control system is working. Coefficient of determination (R^2) is also used to quantify the tracking performance of the proposed controller. The proposed control strategy's gait tracking effectiveness is compared with that of the conventional SMC. Then, using patient-induced disruptions and parameter changes, the controller's performance is evaluated.

Table 2: Performance comparison of SMC and ANFIS-NDO-DSMC

Performance	Stance		Swing	
	SMC	ANFIS-NDO-DSMC	SMC	ANFIS-NDO-DSMC
Rising time(s)	0.045	0.006	0.03	0.006
Settling time(s)	0.06	0.01	0.1	0.01
Steady state error	0.0000005	0.000006	0.00055	0.00003
RMSE	0.000643	0.000516	0.003252	0.00302
R^2	0.9997	1	0.9994	0.9999
Chattering	Exists	Free	Exists	Free

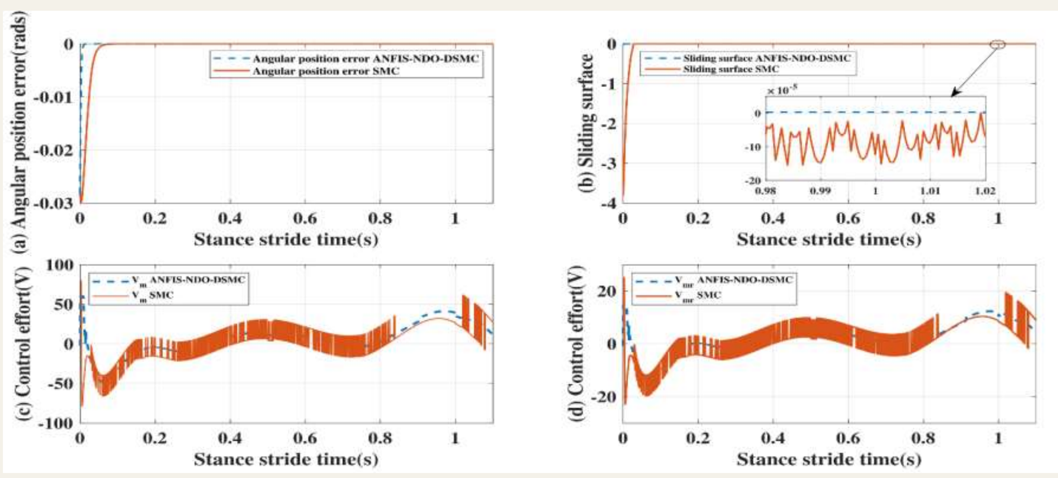

Fig. 5. Stance phase (a) angular position tracking, (b) angular position error, (c) sliding surface and (d) Motor and MR control effort responses using SMC and ANFIS-NDO-DSMC with disturbance and parameter uncertainty

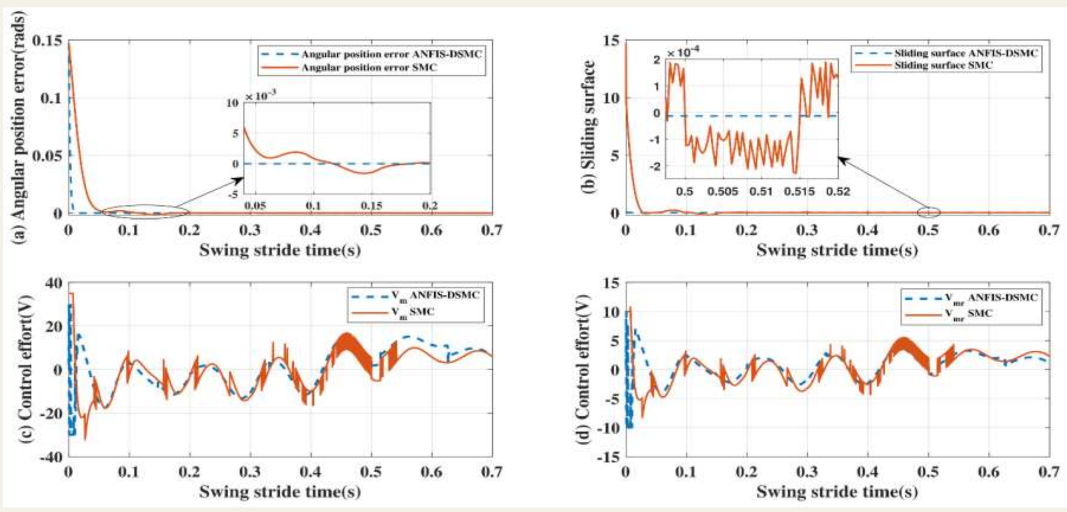

Fig. 6. Swing phase (a) angular position tracking, (b) angular position error, (c) sliding surface and (d) Motor and MR control effort responses using SMC and ANFIS-DSMC with disturbance and parameter uncertainty

Conclusion

ANFIS-NDO-DSMC is employed in this study. By integrating a function that contains the switching control term, the control law is derived. The chattering phenomenon observed in classical SMC is significantly reduced by this integration. Additional dynamics are added by using dynamic sliding mode control. The added dynamics are intended to increase system stability, resulting in the desired system behavior and performance. Dynamic sliding mode control improves precision while also reducing or eliminating chattering brought on by the control's high frequency switching. The ANFIS control approach is utilized to improve the typical knee trajectory tracking performance for parametric fluctuations in the orthotic system. The performance of the proposed controller is verified and excellent trajectory tracking performance is obtained.

References

[1]. S. M. Woolley, "Characteristics of gait in hemiplegia," *Top. Stroke Rehabil.*, vol. 7, no. 4, pp. 1–18, Jan. 2001, doi: 10.1310/JB16-V04F-JAL5-H1UV.

[2]. M. Ackermann and F. G. Cozman, "Automatic knee flexion in lower limb orthoses," *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 31, no. 4, pp. 305–311, Dec. 2009, doi: 10.1590/S1678-58782009000400004.

[3] K. Burnham and A. Zinober, "Dynamic sliding mode control design," no. September 2013, 2005, doi: 10.1049/ip-cta.

[4] J. S. R. Jang, "ANFIS: Adaptive-Network-Based Fuzzy Inference System," *IEEE Trans. Syst. Man Cybern.*, vol. 23, no. 3, pp. 665–685, 1993, doi: 10.1109/21.256541.