INTERVAL TYPE-2 FUZZY LOGIC CONTROL OPTIMIZE BY SPIRAL DYNAMIC ALGORITHM FOR TWO-WHEELED WHEELCHAIR

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DOCTOR OF PHILOSOPHY

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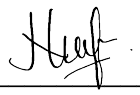
We hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy.



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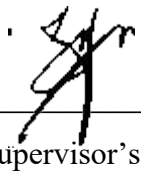

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STABILIZATION CONTROL OF TWO-WHEELED WHEELCHAIR USING SPIRAL DYNAMIC-BASED INTERVAL TYPE-2 FUZZY LOGIC FOR DISABLED/ELDERLY

NURUL FADZLINA BINTI JAMIN

Thesis submitted in fulfillment of the requirements
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DECEMBER 2020

DEDICATIONS

Special dedication to my beloved husband
Jaswari Ismail

Special dedication to my beloved mother
Asmah Muhammad

Special dedication to my beloved father
Jamin Razali

Special dedication to my beloved siblings
Norul Huda, Nurul Hanisah, Mohd Ridzuan Firdaus, Nurul Fadhillah,
Mohd Hiqquan Haqmel, Nurul Syakira, Muhammad Zaquan Naim, Mohd Khairul,
Nurul Saliha, Mohd Hidayat and Mahfuz

Special dedication to my beloved supervisor
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Associate Professor Dr. Zuwairie Ibrahim

Special dedication to my beloved lab mates
Nurnajmin, Noraishah and Firdaus

For your infinite and unfading love, sacrifice, patience, encouragement, best wishes,
for all your care, support, and belief in me.

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ABSTRAK

Konfigurasi semula sistem kerusi roda dua dengan muatan bergerak telah dikaji bagi membolehkan perlaksanaan pelbagai tugas; boleh bergerak ke hadapan dan ke belakang pada permukaan yang rata, boleh mendaki dan menuruni bukit dengan penolakan gangguan yang tidak dikehendaki dan pada masa yang sama ketinggian tempat duduk boleh dilaraskan pada tahap yang maksimum. Kajian penyelidikan ini merangkumi tiga objektif iaitu membina Interval Type-2 Fuzzy Logic Control (IT2FLC) sebagai sistem kawalan, mencipta Spiral Dynamic Algorithm (SDA) untuk IT2FLC dalam menstabilkan sistem kerusi roda beroda dua, dan mengoptimumkan nilai parameter input-output dan parameter kawalan. Sistem beroda dua memberikan banyak kelebihan kepada pengguna seperti memerlukan ruang ruang yang kecil untuk memutar kerusi roda, dapat bergerak di ruang yang sempit, boleh berinteraksi dengan orang normal secara bertentang mata dan dapat mencapai barangan di rak yang lebih tinggi. Walau bagaimanapun, kestabilan sistem beroda dua akan menghasilkan gegaran yang tinggi kerana ketidakpastian ketika menstabilkan sistem dalam kedudukan tegak. Secara tidak langsung, ia juga menyebabkan jarak pergerakan roda yang tinggi dan kedudukan sudut dan tork yang tinggi. Oleh itu, IT2FLC telah diusulkan sebagai strategi kawalan yang sesuai untuk menolak sebarang gangguan bagi mengatasi ketidakpastian agar sistem berada dalam keadaan tegak. Pada dasarnya, IT2FLC menggunakan Set Fuzzy Jenis-2 (T2FS) dan fungsi keanggotaannya (MF) yang terdiri daripada MF rendah, MF atas, dan jejak ketidakpastian (FOU). Ini kerana IT2FLC memiliki kemampuan untuk menangani ketidakjelasan dan ketidakpastian yang berlaku dalam sistem. Oleh itu, sebarang gangguan yang telah diberikan dibelakang kerusi dapat diatasi dengan menggunakan strategi kawalan IT2FLC. SDA digunakan dalam strategi kawalan untuk menentukan nilai optimum bagi parameter kawalan keluar masuk dan parameter IT2FLC yang boleh mengurangkan gegaran pada sistem kerusi roda beroda dua; oleh itu, keselamatan dan keselesaan pengguna dapat dipastikan dengan jarak pergerakan roda yang sedikit, dan tork yang rendah selepas sistem diganggu. Model kerusi roda beroda dua dengan beban bergerak telah direka dalam perisian SimWise 4D (SW4D) untuk mengatasi isu persamaan matematik yang panjang yang telah dipermudahkan dengan membuat beberapa andaian, dan untuk mewakili sistem sebenar kerusi roda serta mengekalkan model dalam keadaan tidak linear dan kompleks. Model humanoid dengan anggaran berat sebanyak 70kg juga digunakan untuk mewakili anggaran purata pengguna dengan mekanisme mengangkat muatan dari 0.11m kepada 0.25m. Kemudian, model yang lengkap diintegrasikan bersama Matlab/Simulink untuk penilaian kawalan dan reka bentuk melalui simulasi visual. Perbandingan telah dibuat diantara pengawal yang dicadangkan dan pengawal sebelumnya, IT2FLC dan Fuzzy Logic Control Type-1 (FLCT1), dalam menilai peningkatan prestasi. Kelebihan SDA-IT2FLC sebagai pengawal kestabilan dalam sistem yang dikaji telah dibuktikan melalui penilaian yang telah dibuat dalam kajian ini dan hasilnya ia mengatasi prestasi pengawal lain (IT2FLC dan FLCT1). Keputusannya menunjukkan pengurangan yang ketara dalam jarak pergerakan roda, kedudukan sudut dan kawalan tork, dengan peningkatan sebanyak 5.6% dan 33.3% bagi kestabilan pautan pertama dan kedua sistem berbanding penalaan heuristic IT2FLC, serta peningkatan sebanyak 60% dan 94% dalam kedudukan sudut pada pautan pertama dan kedua sistem berbanding dengan FLCT1. Selain itu, SDA-IT2FLC juga menunjukkan pengurangan sebanyak 95.4% untuk setiap tork pada sistem berbanding dengan FLCT1. Pada akhirnya, SDA-IT2FLC telah menunjukkan prestasi yang bagus berbanding IT2FLC dan FLCT1 untuk mengekalkan kestabilan sistem dalam kedudukan tegak dari segi penumpuan yang lebih cepat dan pengurangan yang ketara dalam jarak pergerakan roda, kecondongan dan kawalan tork telah membuktikan dirinya sebagai pengawal teguh untuk kerusi roda beroda dua dengan sistem muatan bergerak.

ABSTRACT

The reconfiguration of the two-wheeled wheelchair system with movable payload has been investigated within the current study towards permitting multi-task operations; through enhanced maneuverability on a flat surface under the circumstances of disturbance rejections during forward and backward motions, as well as motions on the inclined surface for uphill and downhill motions; while having height extensions of the wheelchair's seat. The research study embarks on three objectives includes developing Interval Type-2 Fuzzy Logic Control (IT2FLC) as the control system, design a Spiral Dynamic Algorithm (SDA) for IT2FLC in stabilizing the designed double-link two-wheeled wheelchair system, and optimize the input-output gains and control parameters. The two-wheeled system gives lots of benefits to the user such as less space needed to turn the wheelchair, able to move in the narrow spaces, having eye-to-eye contact with normal people, and can reach stuff on the higher shelve. However, the stability of the two-wheeled system will produce high fluctuations due to the uncertainties while stabilizing the system in the upright position. Indirectly, it also caused the long travelled distance and high magnitude of tilt angle and torque. Thus, IT2FLC has been proposed as the compatible control strategy for disturbance rejections to overcome uncertainties for enhanced system stability in the upright position. Basically, IT2FLC uses a Type-2 Fuzzy Set (T2FS) and its membership function (MFs) composed of the lower MFs, upper MFs, and footprint of uncertainty (FOU). This is the reason that IT2FLC possessing the ability to handle cases of nonlinearities and uncertainties that occur in the system. Therefore, any disturbances that give at the back of the seat can be eliminated using the proposed controller, IT2FLC. Additionally, SDA implemented within the control strategy to acquire optimal values of the IT2FLC input-output control gains and parameters of its MFs further accommodated extensive fluctuations of the two-wheeled system; thus, ensuring a safe and comfortable experience among users via shorter traveled distance and lower magnitude of torques following disruptions. The two-wheeled wheelchair is designed using SimWise 4D software to subduing shortcomings of a linearized mathematical model where lengthy equation with various assumptions is required to represent the proposed system; without forgoing its nonlinearity and complexity. Moreover, a 70kg payload was also included to embody an average user, in simulating vertical extensions of the system from 0.11m to 0.25m. The completed model is then integrated with Matlab/Simulink for control design and performance evaluation through visualized simulations. The research has been compared to the previous controllers, Fuzzy Logic Control Type-1 (FLCT1), in gauging improvements and performance superiority. The significance of SDA-IT2FLC as the stability controller within the investigated system has been confirmed through current findings, which outperformed that of its predecessors (IT2FLC and FLCT1). Such results are supported through a significant reduction in traveled distance, tilt, and control torques, following a recorded 5.6% and 33.3% improvements on the stability of the system, to the performance of heuristically-tuned IT2FLC; as well as a 60% and 94% improvements in angular positions on the system, as compared to the FLCT1. Moreover, a 95.4% reduction in torques has been recorded for SDA-IT2FLC, as compared to that of FLCT1. Ultimately, SDA-IT2FLC has demonstrated promising outcomes over its predecessors on maintaining the system's stability in an upright position in terms of faster convergence and a significant reduction in traveled distance, tilt and control torques, proving itself as the robust controller for a double-link two-wheeled wheelchair with movable payload system.

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LIST OF SYMBOLS

Nm	Newton meter
N	Newton
^{o}	Degree
s	Second
m	Meter
cm	Centimeter
kg	Kilogram
%	Percentage
r	Spiral radius
θ	Spiral steps
L_1	Length of 1st pendulum
L_2	Length of 2nd pendulum
θ_0	Cart position
θ_1	Angle amplitude of L_1
θ_2	Angle amplitude of L_2
m_0	Mass of cart
m_1	Mass of L_1
m_2	Mass of L_2
u	Force applied to the cart
$x_{(t)}$	Displacement of cart
$F_{(t)}$	Force applied to the cart
g	Gravitational constant
l	Length of 1st pendulum
M	Mass of the cart
m	Mass of l
θ	Angle of l
z	Position of cart
e	Effort
f	Flow

LIST OF ABBREVIATIONS

LQR	Linear Quadratic Regular
PID	Proportional Integral Derivative
FLCT1	Fuzzy Logic Control Type-1
4D	Four-Dimensional
GA	Genetic Algorithm
COG	Centre of Gravity
PD	Proportional Derivative
SMC	Sliding Mode Control
FLC	Fuzzy Logic Control
IT2FLC	Interval Type-2 Fuzzy Logic Control
MFs	Membership Function
LMF	Lower Membership Function
UMF	Upper Membership Function
FOU	Footprint of Uncertainties
DOF	Degree of Freedom
SW4D	SimWise 4D
SDA	Spiral Dynamic Algorithm
MJLS	Markovian Jump Linear System
GFC	Tuned Fuzzy Controller
NFC	Adaptive Neuro-Fuzzy Controller
MNFC	Modified Neuro-Fuzzy Control
IAE	Integral Absolute Error
LPV	Linear Parameter Varying Controller
LTI	Linear Time-Invariant
RMSE	Root Mean Square Error
RDIP	Rotary Double Inverted Pendulum
FNN	Feed-Forward Neural Network
LM	Levenverg-Marquardt
MSE	Mean Square Error
VN4D	Visual Nastran 4D
PCH	Port-Controlled Hamiltonian

MISO	Multi-Input Single Output
SCD	Stair-Climbing Device
PSO	Particle Swarm Optimization
FTCIT2SM	Finite-Time Convergent Interval Type-2 Fuzzy Logic Sliding
ODMR	Tri-Wheel Omnidirectional Mobile Robot
KM	Karnik-Mendel
HIT2FLC	Hierarchical Interval Type-2 Fuzzy Logic Control
QGA	Quantum Genetic Algorithms
ABC	Artificial Bee Colony Algorithms
CAD	Computer-Aided Design

REFERENCES

Abuelenin, S. M., & Abdel-Kader, R. F. (2018). Closed-form mathematical representations of interval type-2 fuzzy logic systems. *Computer Science Systems and Control*.

Ahmad, S., Siddique, N. H., & Tokhi, M. O. (2011). A modular fuzzy control approach for two-wheeled wheelchair. *Journal of Intelligent and Robotic Systems: Theory and Applications*, *64*(3–4), 401–426. https://doi.org/10.1007/s10846-011-9541-0

Ahmad, S., Siddique, N. H., & Tokhi, M. O. (2012). Modular fuzzy logic controller for motion control of two-wheeled wheelchair. In *Fuzzy Logic – Controls, Concepts, Theories and Applications* (Issue May 2017, pp. 37–58). https://doi.org/10.5772/37584

Ahmad, S., Siddique, N. H., & Tokhi, M. O. (2014). Modelling and simulation of double-link scenario in a two-wheeled wheelchair. *Integrated Computer-Aided Engineering*, *21*(2), 119–132. https://doi.org/10.3233/ICA-130449

Ahmad, S., & Tokhi, M. O. (2008a). Forward and backward motion control of wheelchair on two wheels. *3rd IEEE Conference on Industrial Electronics and Applications*, 461–466. https://doi.org/10.1109/ICIEA.2008.4582558

Ahmad, S., & Tokhi, M. O. (2008b). Modelling and control of a wheelchair on two wheels. *2nd Asia International Conference on Modelling and Simulation*, 579–584. https://doi.org/10.1109/AMS.2008.60

Ahmad, S., & Tokhi, M. O. (2010). Height extension of chair on two-wheeled wheelchair. *12th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines*, 258–265. https://doi.org/10.1142/9789814291279_0034

Ahmad, S., & Tokhi, M. O. (2011). Linear quadratic regulator (LQR) approach for lifting and stabilizing of two-wheeled wheelchair. *4th International Conference on Mechatronics*. https://doi.org/10.1109/ICOM.2011.5937119

Ahmad, S., & Tokhi, M. O. (2013). Steering motion control enhancement scheme of two wheeled wheelchair in confined spaces. *International Journal of Automation and Control Engineering*, *2*(4), 179–189.

Ahmad, S., Tokhi, M. O., & Hussein, Z. (2009). Rejection of yaw disturbance in a two-wheeled wheelchair system. *3rd Asia International Conference on Modelling and Simulation*, 454–459. https://doi.org/10.1109/AMS.2009.65

Ahmad, S., Tokhi, M. O., & Siddique, N. H. (2010). Modular fuzzy control with input shaping technique for transformation of two-wheeled wheelchair to four-wheeled mode. *2010 IEEE Symposium on Industrial Electronics and Applications*, 562–566. https://doi.org/10.1109/ISIEA.2010.5679402

Ahmad, S., Tokhi, M. O., & Toha, S. F. (2009). Genetic algorithm optimisation for fuzzy control of wheelchair lifting and balancing. *3rd UKSim European Modelling Symposium on Computer Modelling and Simulation*, 97–101. https://doi.org/10.1109/EMS.2009.115

Allawi, Z. T., & Abdalla, T. Y. (2015). An optimal defuzzification method for interval type-2 fuzzy logic control scheme. *Science and Information Conference*, 619–627. https://doi.org/10.1109/SAI.2015.7237207

Almeshal, A. M., Goher, K. M., Nasir, A. N. K., & Tokhi, M. O. (2013). Steering and dynamic performance of a New configuration of a wheelchair on two wheels in various indoor and outdoor environments. *18th International Conference on Methods & Models in Automation & Robotics*, 223–228. https://doi.org/10.1109/MMAR.2013.6669910

Almeshal, A. M., Goher, K. M., & Tokhi, M. O. (2013). Dynamic modelling and stabilization of a new configuration of two-wheeled machines. *Robotics and Autonomous Systems*, *61*(5), 443–472. https://doi.org/10.1016/j.robot.2013.01.006

Altalmas, T., Aula, A., Ahmad, S., Tokhi, M. O., & Akmeliawati, R. (2016). Integrated modeling and design for realizing a two-wheeled wheelchair for disabled. *Assistive Technology Journal of RESNA*, *28*(3), 159–174. https://doi.org/10.1080/10400435.2016.1140688

Altalmas, T. M., Ahmad, S., Aula, A., Akmeliawati, R., & Sidek, S. N. (2013). Mechanical design and simulation of two-wheeled wheelchair using solidworks. *International Conference on Mechatronics*, *53*(1). https://doi.org/10.1088/1757-899X/53/1/012042

Anupam, K., & Vijay, K. (2017). Artificial bee colony based design of the interval type-2 fuzzy PID controller for robot manipulator. *IEEE Region 10 Annual International Conference*, 602–607. https://doi.org/10.1109/TENCON.2017.8227933

Aribowo, A. G., Nazaruddin, Y. Y., Joelianto, E., & Sutarto, H. Y. (2007). Stabilization of rotary double inverted pendulum using robust gain-scheduling control. *SICE Annual Conference*, 2, 507–514. https://doi.org/10.1109/SICE.2007.4421037

Aula, A., Ahmad, S., & Akmeliawati, R. (2015). PSO-based state feedback regulator for stabilizing a two-wheeled wheelchair in balancing mode. *10th Asian Control Conference: Emerging Control Techniques for a Sustainable World*, 1–5. https://doi.org/10.1109/ASCC.2015.7244680

Aula, A., Akmeliawati, R., Ahmad, S., Altalmas, T. M., & Sidek, S. N. (2013). Towards port-Hamiltonian approach for modeling and control of two-wheeled wheelchair. *5th International Conference on Mechatronics*, *53*(1). https://doi.org/10.1088/1757-899X/53/1/012074

Aula, A., Altalmas, T. M., Ahmad, S., Akmeliawati, R., Sidek, S. N., & Tokhi, M. O. (2013). Integrated design, modelling and analysis of two-wheeled wheelchair for disabled. *16th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines*, 141–152. https://doi.org/10.1142/9789814525534_0021

Begian, M. B., Melek, W. W., & Mendel, J. M. (2008). Stability analysis of type-2 fuzzy systems. *IEEE International Conference on Fuzzy Systems*, 947–953. https://doi.org/10.1109/FUZZY.2008.4630483

Castillo, O., Amador-Angulo, L., Castro, J. R., & Garcia-Valdez, M. (2016). A comparative study of type-1 fuzzy logic systems, interval type-2 fuzzy logic systems and generalized type-2 fuzzy logic systems in control problems. *Information Sciences*, *354*, 257–274. https://doi.org/10.1016/j.ins.2016.03.026

Castillo, O., Melin, P., Alanis, A., Montiel, O., & Sepulveda, R. (2011). Optimization of interval type-2 fuzzy logic controllers using evolutionary algorithms. *Soft Computing*, *15*(6), 1145–1160. https://doi.org/10.1007/s00500-010-0588-9

Chandran, D., Krishna, B., George, V. I., & Thirunavukkarasu, I. (2015). Model identification of rotary inverted pendulum using artificial neural networks. *International Conference on Recent Developments in Control, Automation and Power Engineering*, 146–150. https://doi.org/10.1109/RDCAPE.2015.7281385

Chotikunnan, P., & Panomruttanarug, B. (2016). The application of fuzzy logic control to balance a wheelchair. *Jornal of Control Engineering and Applied Informatics*, *18*(3), 41–51.

Choura, S., & Yigit, A. S. (2001). Control of a two-link rigid-flexible manipulator with a moving payload mass. *Journal of Sound and Vibration*, *243*(5), 883–897. https://doi.org/10.1006/jsvi.2000.3449

Cosenza, B., & Galluzzo, M. (2011). Experimental comparison of type-1 and type-2 fuzzy logic controllers for the control of level and temperature in a vessel. In *21st European Symposium on Computer Aided Process Engineering* (Vol. 29). Elsevier B.V. https://doi.org/10.1016/B978-0-444-53711-9.50161-9

Duran, K., Bernal, H., & Melgarejo, M. (2008). Improved iterative algorithm for computing the generalized centroid of an interval type-2 fuzzy set. *Annual Conference of the North American Fuzzy Information Processing Society*. https://doi.org/10.1109/NAFIPS.2008.4531244

El-Bardini, M., & El-Nagar, A. M. (2014). Interval type-2 fuzzy PID controller for uncertain nonlinear inverted pendulum system. *ISA Transactions*, *53*(3), 732–743. https://doi.org/10.1016/j.isatra.2014.02.007

El-Nagar, A. M., El-Bardini, M., & El-Rabaie, N. M. (2014). Intelligent control for nonlinear inverted pendulum based on interval type-2 fuzzy PD controller. *Alexandria Engineering Journal*, *53*(1), 23–32. https://doi.org/10.1016/j.aej.2013.11.006

Farooq, U., Gu, J., & Luo, J. (2013). An interval type-2 fuzzy LQR positioning controller for wheeled mobile robot. *EEE International Conference on Robotics and Biomimetics*, *2*, 2403–2407. https://doi.org/10.1109/ROBIO.2013.6739830

Fry, C. (2017). Under-actuated humanoid model with elastomeric springs. *Dynamic Systems and Control Conference*, 1–8. https://doi.org/http://proceedings.asmedigitalcollection.asme.org

Gaines, B. R. (1976). Foundation of fuzzy reasoning. *International Journal of Man-Machine Studies*, *8*(6), 623–668. https://doi.org/10.1016/S0020-7373(76)80027-2

Ghani, N. M. A., Nasir, A. N. K., & Tokhi, M. O. (2014a). Integrated phases modular fuzzy logic control with spiral dynamic optimization for stair descending in a wheelchair. *19th International Conference on Methods and Models in Automation and Robotics*, 46–51. https://doi.org/10.1109/MMAR.2014.6957323

Ghani, N. M. A., Nasir, A. N. K., & Tokhi, M. O. (2014b). Optimization of fuzzy logic scaling parameters with spiral dynamic algorithm in controlling a stair climbing wheelchair: Ascending task. *19th International Conference on Methods and Models in Automation and Robotics*, 776–781. https://doi.org/10.1109/MMAR.2014.6957454

Ghani, N. M. A., & Tokhi, M. O. (2013). A dwi-phase fuzzy control structure for an auto-mode stair climbing wheelchair. *IEEE International Conference on Systems, Man, and Cybernetics*, 4694–4699. https://doi.org/10.1109/SMC.2013.799

Ghani, N. M. A., & Tokhi, M. O. (2016). Simulation and control of multipurpose wheelchair for disabled/elderly mobility. *Integrated Computer-Aided Engineering*, *23*(4), 331–347. https://doi.org/10.3233/ICA-160526

Goher, K. M. K., & Tokhi, M. O. (2010). Genetic algorithm based modeling and control of a two wheeled vehicle with an extended rod, a lagrangian based dynamic approach. *IEEE 9th International Conference on Cybernetic Intelligent Systems*. https://doi.org/10.1109/UKRICIS.2010.5898100

Goher, K. M., & Tokhi, M. O. (2010). A new configuration of two-wheeled inverted pendulum : a Lagrangian-based mathematical approach. *Journal of Selected Areas in Robotics and Control*, 1–5.

Hagras, H. A. (2004). A hierarchical type-2 fuzzy logic control architecture for autonomous mobile robots. *IEEE Transactions on Fuzzy Systems*, *12*(4), 524–539. https://doi.org/10.1109/TFUZZ.2004.832538

Hamza, M. F., Yap, H. J., & Choudhury, I. A. (2015). Recent advances on the use of meta-heuristic optimization algorithms to optimize the type-2 fuzzy logic systems in intelligent control. *Neural Computing and Applications*, *28*, 979–999. https://doi.org/10.1007/s00521-015-2111-9

Hassan, M. Y. (2018). Intelligent tracking control using PSO-based interval type-2 fuzzy logic for a MIMO maneuvering system. *Al-Qadisiyah Journal for Engineering Sciences*, *11*(1), 22–39. https://doi.org/10.30772/qjes.v11i1.518

Henmi, T., Deng, M., Inoue, A., Ueki, N., & Hirashima, Y. (2004). Swing-up control of a serial double inverted pendulum. *Proceedings of the American Control Conference*, *5*, 3992–3997. https://doi.org/10.23919/acc.2004.1383932

Hsiao, M. Y., Chen, C. Y., & Li, T. H. S. (2008). Interval type2 adaptive fuzzy sliding-mode dynamic control design for wheeled mobile robots. *International Journal of Fuzzy Systems, 10*(4), 268–275. https://doi.org/https://www.researchgate.net/publication/241418754

Hsiao, M. Y., & Wang, C. T. (2013). A finite-time convergent interval type-2 fuzzy sliding-mode controller design for omnidirectional mobile robots. *International Conference on Advanced Robotics and Intelligent Systems*, 80–85. https://doi.org/10.1109/ARIS.2013.6573539

Hsu, P. E., Hsu, Y. L., Lu, J. M., & Chang, C. H. (2013). Seat adjustment design of an intelligent robotic wheelchair based on the stewart platform. *International Journal of Advanced Robotic Systems*, *10*(168). https://doi.org/10.5772/55880

Kulkarni, A. G., Qureshi, M. F., & Jha, M. (2014). Genetically tuned interval type-2 fuzzy logic for fault diagnosis of induction motor. *International Journal of Innovative Research in Science, Engineering and Technology*, *3*(7), 14890–14899. https://doi.org/http://www.ijirset.com/upload/2014/july/87_Genetically.pdf

Martínez, R., Castillo, O., & Aguilar, L. T. (2009). Optimization of interval type-2 fuzzy logic controllers for a perturbed autonomous wheeled mobile robot using genetic algorithms. *Information Sciences*, *179*(13), 2158–2174. https://doi.org/10.1016/j.ins.2008.12.028

Melgarejo, M. (2007). A fast recursive method to compute the generalized centroid of an interval type-2 fuzzy set. *Annual Conference of the North American Fuzzy Information Processing Society*, 190–194. https://doi.org/10.1109/NAFIPS.2007.383835

Mendel, J. M., & Liang, Q. (2000). Interval type-2 fuzzy logic systems: Theory and design. *IEEE Transactions on Fuzzy Systems*, *8*(5), 535–550. https://doi.org/10.1109/91.873577

Mendel, J. M., & Liu, F. (2007). Super-exponential convergence of the Karnik-Mendel algorithms for computing the centroid of an interval type-2 fuzzy set. *IEEE Transactions on Fuzzy Systems*, *15*(2), 309–320. https://doi.org/10.1109/TFUZZ.2006.882463

Mitschka, C. M., Terra, M. H., & Siqueira, A. A. G. (2015). Derivation of a markovian controller for an exo-skeleton by overcome the benchmarks of a single and double inverted pendulum. *IEEE Conference on Decision and Control*, 5061–5066. https://doi.org/10.1109/CDC.2015.7403011

Mohan, V., Rani, A., & Singh, V. (2017). Robust adaptive fuzzy controller applied to double inverted pendulum. *Journal of Intelligent and Fuzzy Systems*, *32*(5), 3669–3687. https://doi.org/10.3233/JIFS-169301

Moysis, L. (2016). Balancing a double inverted pendulum using optimal control and Laguerre functions. *Technical Report Research Gate*. https://doi.org/10.13140/RG.2.1.2948.6486

Naik, K. A., & Gupta, C. P. (2017). Performance comparison of type-1 and type-2 fuzzy logic systems. *4th IEEE International Conference on Signal Processing, Computing and Control*, 72–76. https://doi.org/10.1109/ISPCC.2017.8269652

Nie, M., & Tan, W. W. (2008). Towards an efficient type-reduction method for interval type-2 fuzzy logic systems. *IEEE International Conference on Fuzzy Systems*, *2*, 1425–1432. https://doi.org/10.1109/FUZZY.2008.4630559

Piovesan, D., Yagiela, M., Johnson, R., & Schmitz, A. (2016). Combining gait trainers and partial weight bearing lifters : A dynamic analysis of seat-to-stand transition. *Dynamic Systems and Control Conference*. https://doi.org/10.1115/dscc2016-9731

Qian, Q., Wu, J., & Wang, Z. (2017). A novel configuration of two-wheeled self-balancing robot. *Technical Gazette*, *24*(2), 459–464. https://doi.org/10.17559/TV-20160608105436

Reilly, T., O'Rourke, J. K., Steudler, D., Piovesan, D., & Bortoletto, R. (2016). *Locomotive Underactuated Implement Guided via Elastic Elements (L.U.I.G.E.E): A Preliminary Design*. *August*, V003T03A067. https://doi.org/10.1115/imece2015-50567

Ri, M., Huang, J., Ri, S., Yun, H., & Kim, C. (2016). Design of interval type-2 fuzzy logic controller for mobile wheeled inverted pendulum. *Proceedings of the World Congress on Intelligent Control and Automation*, 535–540. https://doi.org/10.1109/WCICA.2016.7578403

Robert, J., & Coupland, S. (2007). Type-2 fuzzy logic: A historical view. *IEEE Computational Intelligence Magazine*, *2*(1), 57–62. https://doi.org/10.1109/MCI.2007.357194

Shill, P. C., Amin, M. F., Akhand, M. A. H., & Murase, K. (2012). Optimization of interval type-2 fuzzy logic controller using quantum genetic algorithms. *IEEE International Conference on Fuzzy Systems*, 10–15. https://doi.org/10.1109/FUZZ-IEEE.2012.6251207

Siddique, N., & Adeli, H. (2017). Spiral Dynamics Algorithms. *Nature-Inspired Computing*, *23*(6), 329–362. https://doi.org/10.1201/9781315118628-7

Simpson, R. C. (2005). Smart wheelchairs : A literature review. *Journal of Rehabilitation Research and Development*, *42*(4), 423–435. https://doi.org/10.1682/JRRD.2004.08.0101

Singh, N., & Yadav, S. K. (2012). Comparison of LQR and PD controller for stabilizing double inverted pendulum system. *International Journal of Engineering Research and Development*, *1*(12), 69–74. https://doi.org/10.1.1.300.1993

Strah, B., & Rinderknecht, S. (2014). Hybrid dynamic model of a wheeled double inverted pendulum. *22nd Mediterranean Conference on Control and Automation*, 1305–1310. https://doi.org/10.1109/MED.2014.6961556

Tamura, K., & Yasuda, K. (2011). Spiral dynamics inspired optimization. *Journal of Advanced Computational Intelligence and Intelligent Informatics*, *15*(8), 1116–1122. https://doi.org/10.20965/jaciii.2011.p1116

Tamura, Kenichi, & Yasuda, K. (2011). Primary study of spiral dynamics inspired optimization. *IEEJ Transactions on Electrical and Electronic Engineering*, *6*(1), 2010–2012. https://doi.org/10.1002/tee.20628

Wu, D. (2013). Approaches for reducing the computational cost of interval type-2 fuzzy logic systems: Overview and comparisons. *IEEE Transactions on Fuzzy Systems*, *21*(1), 80–99. https://doi.org/10.1109/TFUZZ.2012.2201728

Wu, D., & Mendel, J. M. (2009). Enhanced Karnik – Mendel algorithms. *IEEE Transactions on Fuzzy Systems*, *17*(4), 923–934. https://doi.org/Enhanced Karnik – Mendel algorithms

Wu, D., & Nie, M. (2011). Comparison and practical implementation of type-reduction algorithms for type-2 fuzzy sets and systems. *IEEE International Conference on Fuzzy Systems*,2131–2138. https://doi.org/10.1109/fuzzy.2011.6007317

Wu, H., & Mendel, J. M. (2002). Uncertainty bounds and their use in the design of interval type-2 fuzzy logic systems. *IEEE Transactions on Fuzzy Systems*, *10*(5), 622–639. https://doi.org/10.1109/TFUZZ.2002.803496

Yadav, S. K., & Singh, M. N. (2012). Optimal control of double inverted pendulum using LQR controller. *International Journal of Advanced Research in Computer Science and Software Engineering*, *2*(2), 189–192.

Yang, H. C. (2017). Using an imaginary planar rack cutter to create a spherical gear pair with continue involute teeth. *Arabian Journal for Science and Engineering*, *42*(11), 4725–4735. https://doi.org/10.1007/s13369-017-2630-z

APPENDIX A :
LIST OF PUBLICATIONS

Journals:

Jamin, N. F., Ghani, N. M. A., Ibrahim, Z., Nasir, A. N. K., Rashid, M. & Tokhi, M. O. (2020). Stabilizing control of two-wheeled wheelchair with movable payload using optimized interval type-2 fuzzy logic. Journal of Low Frequency Noise, Vibration & Active Control (ISI Journal Q1, I.F 4.59).

Jamin, N. F., Ghani, N. M. A. & Ibrahim, Z. (2020). Movable payload on various conditions of two-wheeled double links wheelchair stability control using enhanced interval type-2 fuzzy logic. IEEE Access 8, 87676-87694 (ISI Journal Q1, I.F 4.098).

Jamin, N. F., Ghani, N. M. A., Ibrahim, Z., Almeshal, M. A., Masrom, M. F. & Razali, N. A. A. (2018). Two-wheeled wheelchair stabilization using interval type-2 fuzzy logic controller. International Journal of Simulation Systems, Science & Technology, 19, 31-37.

Maharuddin, M. F., Ghani, N. M. A. & **Jamin, N. F.** (2017). Two-wheeled LEGO EV3 robot stabilization control using fuzzy logic based PSO algorithm. Journal of Telecommunication, Electronic and Computer Engineering, 10(2-5), 149-153.

Lecture notes:

Jamin, N. F., Ghani, N. M. A., Ibrahim, Z., Masrom, M. F. & Razali, N. A. A. (2019). Stabilization of two-wheeled wheelchair with movable payload based interval type-2 fuzzy logic controller. Proceedings of the 10th National Technical Seminar on Underwater System Technology, Lecture Notes in Electrical Engineering, 538, 137-149.

Masrom, M. F., Ghani, N. M. A., **Jamin, N. F.** & Razali, N. A. A. (2019) Stabilization control of a two-wheeled triple link inverted pendulum system with disturbance rejection. Proceedings of the 10th National Technical Seminar on Underwater System Technology, Lecture Notes in Electrical Engineering, 538, 151-159.

Conference:

Jamin, N. F. & Ghani, N. M. A. (2016). Two-wheeled wheelchair stabilization control using fuzzy logic controller based particle swarm optimization. IEEE International Conference on Automatic Control and Intelligent Systems, 180-185.

Akmal, M. A., **Jamin, N. F.** & Ghani, N. M. A. (2017). Fuzzy logic controller for two wheeled EV3 LEGO robot. IEEE Conference on Systems, Process and Control, 134-139.

Masrom, M. F., Ghani, N. M. A., **Jamin, N. F.** & Razali, N. A. A. (2018). Control of triple link inverted pendulum on two-wheeled system using IT2FLC. IEEE International Conference on Automatic Control and Intelligent Systems, 29-34.

Razali, N. A. A., Ghani, N. M. A., **Jamin, N. F.** & Masrom, M. F. (2018). Stability control of wheelchair system using interval type-2 fuzzy logic control (IT2FLC). 9th IEEE Control and System Graduate Research Colloquium, 162-167.

Kii, M. S. C., Masrom, M. F., **Jamin, N. F.,** Razali, N. A. A. & Ghani N. M. A. (2019). Interval type-2 fuzzy logic with particle swarm optimization for DC motor position control. 22nd International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines.

Kin, W. S., Masrom, M. F., **Jamin, N. F.,** Razali, N. A. A. & Ghani, N. M. A. (2019). Control of a two-wheeled LEGO EV3 robot using interval type-2 fuzzy logic with particle swarm optimization. 22nd International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines.