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Forkloader Position Control for A Mini Heavy Loaded Vehicle using Fuzzy Logic-Antiwindup Control

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Abstract

This paper presents a proposed integrated Takagi-Sugeno-Kang (TSK) type Fuzzy Logic control (TSK-FLC) with Antiwindup elements for a forkloader position control of a Mini Heavy Loaded Forklift Autonomous Guided Vehicle (MHeLFAGV). The study was carried out by modeling TSK-FLC as a close-loop control for the each axis of the fork-lift's movement. The degree of membership is designed with reference to the system response, in which ultrasonic sensor with 1cm resolution is used. Moreover, the rule base is determined and optimized to deal with microcontroller processing speed. In order to cater for the windup phenomenon, proportional and integrated antiwindup elements are integrated into the TSK-FLC model. This control strategy consumes less memory and is expected to increase the time response of the control system. The experiment and analysis is done on the actual forkloader unit of MHeLFAGV system. The experiment was done on the vertical axis motion since horizontal motion will have the same characteristic pattern of implementation and characteristic of tuning. The experiment shows that the proposed integrated TSK-FLC with antiwindup elements is able to speed up the time response of the system and eliminate the overshoot as well as oscillation on the forkloader movement.

Keywords: *precision control, fuzzy logic, antiwindup*

1. Introduction

Forklift trucks are commonly used in heavy duty operations, especially in factory warehouses, inventory stores, cargos, etc. With the emergence of new technology, such as Automated Guided Vehicle (AGV) and Remotely Controlled Vehicle (RCV), the forklift truck will be able to be automatically operated with programmed instruction or remotely controlled by humans, over short or long distances. However, most of the available AGVs/RCVs in the market are for certain standard size working area, which sometimes is unable to meet the user requirement, particularly for a confined and narrow area. Our collaborator, Vacuumshmelze (M) Sdn. Bhd., located in Pekan, Pahang, encountered a problem in that they require a customized AGV/RCV unit to operate in a very confined warehouse (track size 170cm x 286cm) with payload ranging from 20 - 200kg. Consequently, a customized RCV unit, with the capability of pick-and-place 20 - 200kg spool in each rack system, has been developed in their warehouse. This mini-RCV, named Mini Heavy Loaded Forklift Autonomous Guided Vehicle (MHeLFAGV), was designed and configured with mecanum wheels mechanisms and 2-axis Forkloader to pick-and-place the spool inventory at the targeted places. Other than the overall movements of the fork-loader, its' aligning and picking motions need to be precise. To achieve precision of motion, a stable and robust close-loop control design can be employed as an alternative solution other than component replacement with high-end specifications. In contrast, the open-loop control scheme lacks load adaptability, and uncertainties making the system unreliable.

Proportional, Integral and Derivative (PID) controller is commonly used in industrial machine systems that require very minimum plant information and is reliable for real-time system alication. However, traditional PID control algorithm cannot take into consideration the

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nonlinear factors due to saturation, and the implementation of a PID controller designed using conventional methods performs worse than expected [1]. Several adaptive efforts have been carried out on PID control, and PID as adaptive elements has been used in some intelligent control design, such as Fuzzy logic control (FLC), Neural Network (NN), and Swarm intelligent. Elsodany et al. used fuzzy logic in PID control to optimise gain scheduling when controlling a permanent magnet steer motor for a flexible rotor drive; conventional PID control was unable to stabilize the load speed response performance with variable load inertia [2]. Other adaptive PID control, such as Model Pridictive Control with PID [3], Genetic Algorithm and Fire Fly Algorithm with PID [3], Least Squares Suort Vector Machines (LSSVM) identifier PID [4] and NN-based PID [5], also show positive improvement over the classical control implementation, either mathematically or in actual system feasible studies and experiments. The integral windup, also known as reset windup, refers to the phenomenon of PID feedback controller that occurs when a big change haened in the reference and the integrator produces a notable error during rise-time (windup). The change produces an overshoot that causes the peaks of the control signal to be higher than the reference signal [1], such as stated in [3], and the strong output oscillations could cause the system to require a longer duration to reach steady-state condition. Consequently, anti-windup PID is designed and implemented to control the amount of control output so that it will not go beyond the standard operating range, while maintaining in the saturated zone [1]. In the case of real-time control alication, iterative factor is needed to minimize or eliminate the overshoot as much as possible since it will affect the overall processing time that could lead to the slow time responses. FLC is one the intelligent control that is suitable to be implemented in real-time system, and is commonly integrated with PID elements. As for example, PD-FLC is capable of rejecting the noise signal with minimum control tuning, such as reported in [6-10].

In this study, an improved method of the control was investigated and implemented by integrating Takagi-Sugeno-Kang (TSK) FLC with Antiwindup elements in order to increase the motion precision of MHeLFAGV Forkloader. The investigation is focused on the feasibility of TSK-FLC for a high power direct-current (DC) motor drive of high-loaded forklift carriage and to evaluate its sensitivity to mechanical motion changes for both axes. The improvement was done on the TSK-FLC structure by adding the anti-windup elements, in addition to minimizing the rule-based of FLC itself. This aroach is done to optimize the system processing and improve the time response of the Forkloader unit positioning. Several experiments were conducted on the actual MHeLFAGV Forkloader unit without load, with both session TSK-FLC with and without Antiwindup elements.

2. Overview on MHeLFAGV System and Forklift Configuration

The unavailability of a commercial AGV system that can be employed in the targeted confined area and to cope with the heavy loads became the motivation for the development of MHeLFAGV. The system currently being developed will have the capability to be remotely controlled using wireless technology, and the system will be sufficient to be used in the targeted warehouse. As shown in Figure 1, mecanum wheels with an overall size of 996mm x 700mm is used for this vehicle, and the forklift unit is placed on the left side of its structure in order to balance the whole vehicle. Moreover, the system is expected to be able to load, unload and transfer a heavy coer spool from point to point with flexible movement. The system consists of three main components: Direct-Current (DC) motor controller, Radio Frequency (RF) remote controller, and four industrial grade DC motors.

On the Forkloader unit system, the grasping-and-swallowed mechanism is alied (patent alied), in which the load is kept inside the main body while the fork-loader is travelling or transferring its load. This mechanism is designed to ensure the loaded item is properly grasped and placed inside the MHeLFAGV's body to retain the center-of- gravity (CoG) of the vehicle during movement and to ensure the safety of inventory loging (quality assurance). A 2-axis Forkloader system is designed for the MHeLFAGV system, as shown in Figure 2. The motion of the two axes allows loading and unloading of the picked material; the Y-axis is used to elevate or lift the fork-loader, while the X-axis is used to move the fork-loader inside and out of the MHeLFAGV's body, as shown in Figure 2(c). This movement is different from that found in the common forklift system, in which the four wheels need to move forward or backward to get closer to the load (non-holonomic mechanism). On the other hand, as shown in Figure 2(a), ball-screw rotation is used in MHeLFAGV's Forkloader unit since the targeted payload is between 50kg and 200kg. With reference to Figure 2, the motion and movement of the fork-loader is driven by a ball screw that is connected to shaft of the DC motor.

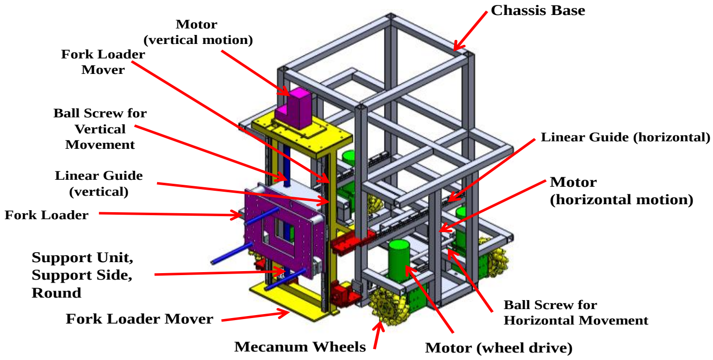

Figure 1. Overview of MHeLFAGV system

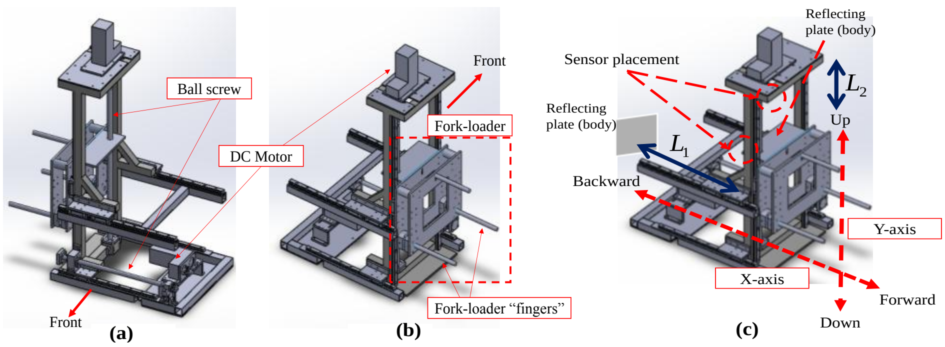

Figure 2. MHeLFAGV's Forkloader system overview: (a) 3D front view, (b) 3D rear view (c) Grasping-and-Swallowed mechanism and sensor configuration

Table 1. The main components configured in Fork-Loader control system of MHeLFAGV

Component	Brand	No. of unit	Remarks
High current DC Motor	AmpFlow EF30-400	2	Geared Motor, 24V DC
Sensor	HC-SR04	2	1cm resolution, 5V DC
Motor Driver	Roboteq XDC2460	1	Dual Channels, 60V DC
Microcontroller	Arduino Mega 2560	1	5V DC

As shown in Table 1, ultrasonic HC-SR04 with range from 2cm to 400cm (1cm resolution) is used as a feedback for each axis of the Forkloader motion. These ultrasonic sensors are attached as shown in Figure 2(c), and are used to measure the distance between the fork-loader and the reflecting plates. The sensors are placed along both axes, such that the beam of the sensor faces the reflection plate, and the plate is used to reflect the Ping sound back to the sensor. As shown in Figure 2(c), L_1 and L_2 are notified as the distance measured by the ultrasonic sensor for Y- and X-axis, respectively.

3. Proposed PI-Windup-FLC for MHeLFAGV Forkloader Axis Motion Precision

As mentioned in the previous section, a Takagi-Sugeno-Kang (TSK) type FLC is used for each MHeLFAGV's Forkloader precision control. This FLC is designed with multiple inputs and single output (MISO) crisp error for the distance of each axis motion by considering two state orders: ΔE and $\Delta\dot{E}$. The error for each axis of Forkloader is expressed as Equation 1.

$$(E_x(\mathrm{t}), E_y(\mathrm{t})) = \begin{Bmatrix} R_x - F_x \\ R_y - F_y \end{Bmatrix} \tag{1}$$

Where Fx and Fy are the feedback measured data from the distance sensors for the axis motion L1 and L2, respectively, as shown in Figure 2(c)._Three steps taken in developing the FLC, as shown in Figure 4, are fuzzification, fuzzy rules (inference mechanism and rule base) and defuzzification. The continuous fuzzy model proposed by [11] is used via fuzzy *if-then* rules to optimize the input variables. The fuzzy rule base containing i^{th} rules for a multi-input single-output (MISO) fuzzy system with the following form [9] is considered as follows:

$$if \;\; h_1 \;\; is \;\; M_1^i \;\; and ... if \;\; h_k \;\; is \;\; M_k^i \;\; then \;\; H^i \tag{2}$$

Where $h_k \in \Re^k$ are the system state variables, M_k^i are the fuzzy sets, and H^i are the outputs characterized in linguistic terms, that is, SMALL (S), MEDIUM (M), and BIG (B) for both positive (P) and negative (N) coordination. The final output, or crisp output, of the fuzzy system (u) controller is inferred as follows (using a singleton fuzzifier with a minimum operator as the antecedent part of the rules (Π) and the center of mass method for defuzzification) as expressed in Equation 3:

$$u_s(t) = \frac{\sum_{i=1}^{I^s} \varepsilon[\Pi_{a=1}^2 \mu_a(\lambda_a E_s(t))]}{\sum_{i=1}^{I^s} \Pi_{a=1}^2 \mu_a^i(\lambda_a E_s(t))} \tag{3}$$

Where, I^i is the number of rules selected from the total of i^{th} rules that are present in the rule base for a set of inputs; λ_a is the feedback compensator that claimed with K_p and K_D values, in this case study $E(t) = \{E_x(\mathrm{t}), E_y(\mathrm{t})\}$ as an input variable (which must satisfy $E(t) > 1$); ε is the scaling factor for each defined membership function, that is, degree of membership function from 0 to 1 that are Negative Big (neB), Negative Small (neS), Zero (Ze), Positive Small (poS) and Positive Big (poB) as shown in Figure 5. The minimum and maximum value for each input are -1 and 1, respectively, thus the saturation will convert any exceeded value into the set range where $\varepsilon = 1$. In addition, $\mu_a(\dot{v}(t))$ is the membership function value for the $E(t)$ input variables, where it represents different values for different *s*. Constant value is set for each membership function as shown in Table 2. For the first setting in the design, 25 rules (condition) are used to create outcome as TSK-FLC control input $u(t)$ since there are five memberships for both inputs crisp. The inference created using AND method, where the lowest degree of membership functions between $f(e)$ and $f(de/dt)$ are chosen for every rule. This TSK-FLC system is extended with adaptive elements to cater the windup phenomenon using Proportional-Integrated (PI) Antiwindup method, in which $u(t)$ is back calculated. The expectation of this integration is to eliminate overshoot in Forklift first move, whereby integral state, $\Delta\dot{E}$ to be recalculated to a new value that produce an output when the system reach to its saturation limit [12]. As shown as Figure 4, the PI Antiwindup element is added to reproduce new antiwindup $u(t)$, which can be expessed in Equation 4:

$$U(t) = K_p E(t) + \sum_{t=t-T}^{t} \left(K_i K_p E(t) + \Delta u(\mathrm{t}) \mathrm{K}_T \right) K_{TS} \tag{4}$$

Where $\Delta u(t)$ is the updated change of TSK-FLC controller output, $K_{TS} = T^{-1}$ which $T = 1ms$ of the processing unit sampling time, K_i is a integral gain, and K_T is a back signal control input gain. All this gain tuning is done during the experimental session on actual system of MHeLFAGV Forkloader unit as explained in Section 3 of the paper

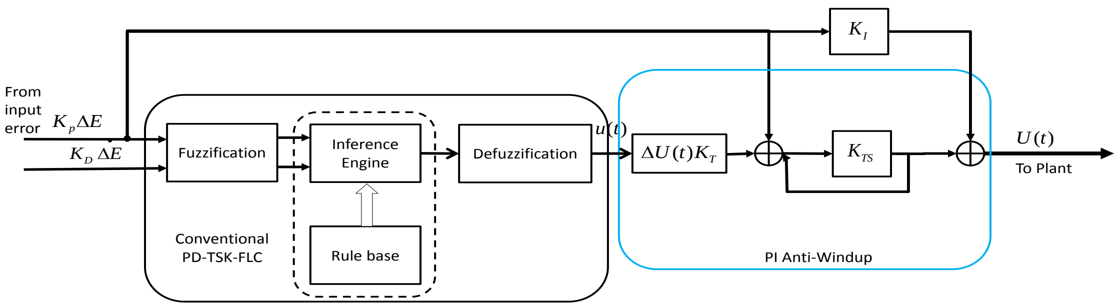

Figure 4. Block diagram of the proposed PI-Windup-FLC control system for MHeLFAGV Forkloader positioning control

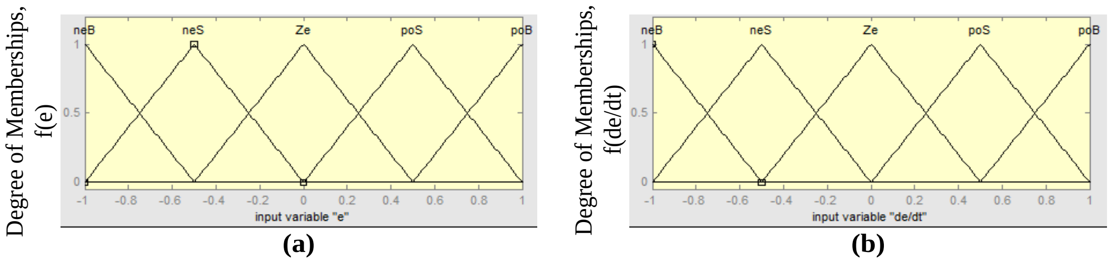

Figure 5. Memberships design for each crisp input using Trapezium Shape (a) Input of ΔE represented by $f(e)$, (b) Input of $\dot{\Delta E}$ represented by $f(de/dt)$

Table 2. Constant for each output membership function of the designed TSK-FLC

Constant f(u)	Value
neB	-1.0
neS	-0.5
Ze	0
poS	0.5
poB	1.0

Table 3. First setting of rule base for the MHeLFAGV Forkloader motion precision

de/dt \ e	neB	neS	Ze	poS	poB
neB	poB	poB	poB	poS	Ze
neS	poB	poB	poS	Ze	neS
Ze	poB	poS	Ze	neS	neB
poS	poS	Ze	neS	neB	neB
poB	Ze	neS	neB	neB	neB

4. Results and Analysis

To verify the the proposed Antiwindup with TSK-FLC, several experiments were conducted to observe the performance and effect on the axis motion precision of MHeLFAGV Forkloader. The emphasis of the experiments is on Y-axis motion performance; similar method was alied on the X-axis using different parameter tuning. A repeating sequence stair signal is used to generate the reference or desired position, with gap distance ranging from 25cm to 50cm from the ultrasonic sensor. The experiment was done in two sessions with the same desired input: Y-axis movement with TSK-FLC, and Y-axis with Antiwindup-TSK-FLC (A-TSK-FLC). Some fine tuning was done on each tuning parameters, such as K_p and K_D for TSK-FLC and, K_i and K_T, for A-TSK-FLC. As shown in Figure 6, the experiment is done and analyzed in two cases: Y-axis movement from 25cm point to 50cm and vice versa.

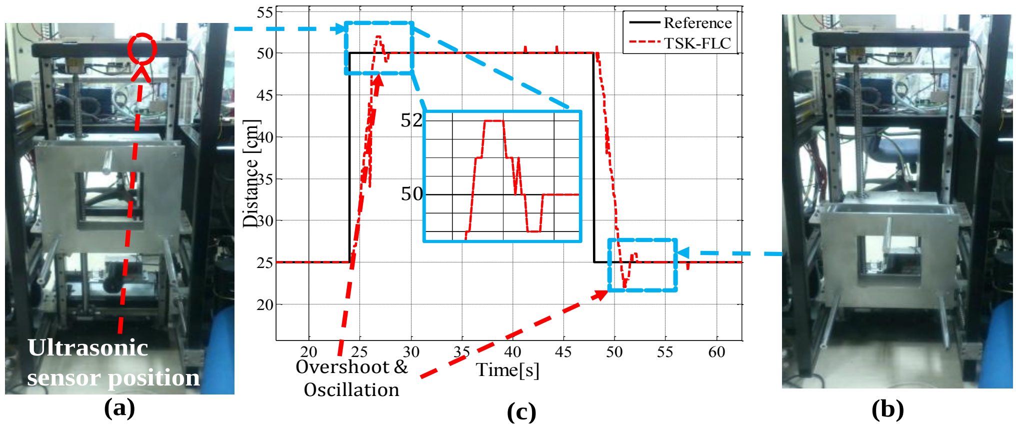

Figure 6. Experimental setting for Fork-Loader Y-Axis Position from MHeLFAGV top frame (a) Move from 25cm to 50cm, (b) Move from 50cm to 25cm, (c) Fork-Loader position performances before FLC implementation

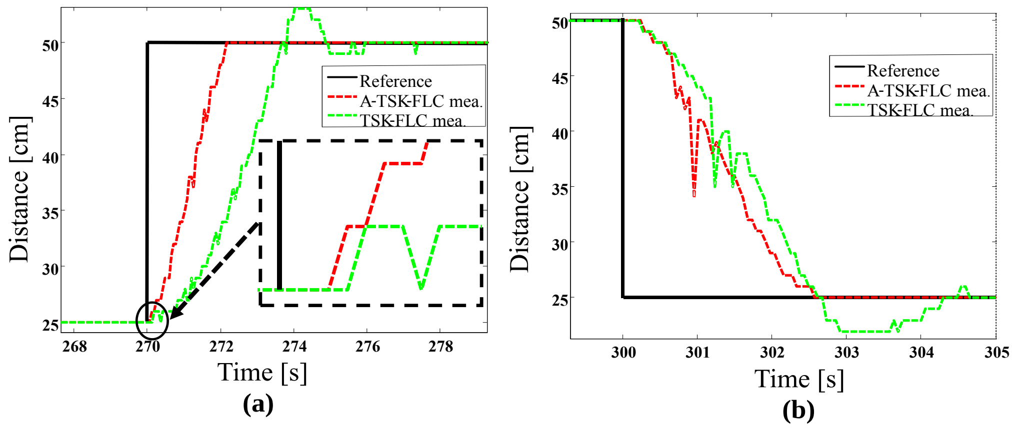

Figure 7. A-TSK-FLC (red) versus TSK-FLC (green) Y-axis experiment sample: (a) for motion from 25cm to 50cm positioning, (b) for motion from 50cm to 25cm positioning

For the case of movement from 25cm to 50cm, A-TSK-FLC settling time is able to response 3.7s faster than that of the Y-axis motion with TSK-FLC, as shown in Figure 7. Also, the overshoot that occurred in the case of TSK-FLC causes instability in its operation, which amounts to about 80% from the steady state position. Morever, the oscillation that produce swinging on Forkloader unit its quite decay the settling time for this running, which is take about 6sec from the first move. It is different to the A-TSK-FLC running whereby almost no overshoot occurred when the Forkloader unit achieved 50cm point from distance sensor. On the other hand A-TSK-FLC running able to achieve settling time is 3.7s faster than TSK-FLC. Almost same situation occurred for the case of positioning from 25cm to 50cm point. TSK-FLC and A-TSK-FLC operate in the same manner in terms of time response; however, as shown in Figure 7, an overshoot of about -50% from the desired position occurred when operating in TSK-FLC, may risk the loaded item. Also, due to the overshoot, oscillation also occurred in this point of positioning for the case of Y-axis movement with TSK-FLC, in which the settling time is delayed by about 2.1s compared to that of the A-TSK-FLC.

5. Conclusion

This paper has presented the implementation of the proposed integrated Antiwindup TSK-FLC for MHeLFAGV Forkloader. Through a series of laboratory tests, it is found that both techniques, TSK-FLC and A-TSK-FLC, are suitable to be implemented for Forkloader unit positioning. The A-TSK-FLC performed better that TSK-FLC as its response is faster and produces almost zero overshoot on Forkloader positioning. In terms of rising time, operating in A-TSK-FLC is 1.5s faster than operating in TSK-FLC for the case of positioning from 25cm to 50cm point. Similarly, the delaying time operating in TSK-FLC is delayed by aroximately 0.06s when positioning from 25cm to 50cm compared to that when operating in A-TSK-FLC. The oscillation that occurred during TSK-FLC operation has resulted in longer settling time, compared to that when operating in A-TSK-FLC, might overdrive the Forkloader unit. Moreover, the overdriven situation not only affects the accuracy for fork-lift component but also pose some risks to the loaded item. The next stage of the project is to design and develop a precise desire input positioning of the Forklif component via vision sensing or image processing associated with A-TSK-FLC in pick-and-place task.

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