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Research Article

Force Feedback Control System for a Virtual Tank Driving Simulator

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Abstract:
The virtual force feedback system has not been implemented in most tank driving simulators which provide less realistic and less effectiveness of army personnel training. M60A3 tanks have been a prevalent tank for many decades but the information of military tanks was mystery, and has rarely been presented or published. Force exerted by a driver to the driving mechanism of a tank vehicle could be varied due to model uncertainty. The dynamics of a mechanical mechanism, which combines the rotational motion, static friction, sliding friction, and fluid friction, is considered. This paper presented the systematic technique to collect the force information and design force feedback system for a virtual tank driving simulator. Force measurements were applied for collecting the force exerted by drivers on the gas pedal, the brake pedal, and the handlebar of the tank. The force data is the reference data for designing the virtual tank driving simulator. The tank's driving mechanisms with force feedback systems, those are a brake pedal, a gas pedal and a handlebar, were developed. The force sensors were used as feedback signals to control industrial servo motors to generate resistance forces as the original M60A3 tank. Vehicle dynamic model was implemented to the virtual driving simulator as vehicle system integration as Hardware-in-the-loop (HIL). The force feedback control system generated the maximum force as 214.06 N. and 466.78 N. on gas pedal, and brake pedal, respectively as the actual M60A3 tank which the errors are less than 3%.

Keywords: *Force feedback system, Simulation platform, Force control, Hardware-in-the-Loop, Military tank*

1. Introduction

In army personnel training, tank driving simulators were typically used for military education and training which allow the personnel to become familiar with the battle. The virtual force feedback system has not been implemented in most simulators which provide less realistic and less effectiveness of training. Force feedback system is an important feature of the virtual training system that makes the trainees feels (immersive) like practicing with the real system. Vehicle dynamic model of a tank, such as suspension, can be defined as a set of rigid bodies connected to powertrain components and ground [1]. The problem of the tracked vehicles dynamics modelling is a complex issue, due to difficulties in the identification of system models; such as optimizing stiffness and damping characteristics of vehicle suspension.

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In research and development of force feedback for a virtual driving simulator, the driving mechanisms must be designed together with the system control scheme. Nagai et al., [2] developed a double-driver (long ladder-style) fire-truck simulation with a tiller (rear steering), driven via an integrated pair of networked driving simulator stations. The dual-driver system is useful to turn narrow corners rapidly and smoothly in case of (simulated) emergencies. The force feedback steering wheels display simple collision force to both drivers separately when the vehicle collides with walls or other vehicles.

The braking in automobiles is a hydraulic system that responds to braking force and drives resistance to a brake pedal. In [3], an electric motor is used to create a virtual resistance force from the brake pedal back to the foot to present the occurrence of braking. The research created a model using differential equations and tested it in the frequency domain and time domain. The control system applied two linear actuators with disturbance observer and reaction force observers to provide pedal force amplification, pedal retraction capabilities, and force controller to provide pedal feel to drivers.

In [4], an active brake pedal simulator was introduced to achieve desired brake feel using closed loop force control. A torque sensor and a geared DC motor are employed for explicit force control of the brake pedal. In [5], resistive force was applied by selectively immobilizing the base of a spring. In [6], force-feedback brake pedal with series elastic actuation was designed to preserve the conventional brake pedal feel during cooperative regenerative braking. Feed-forward control generated the force ejected on the brake pedal by the driver for the brake feel. The applicability and effectiveness of the system have been tested through human subject experiments that evaluate simulated cooperative regenerative braking scenarios with and without pedal feel compensation.

In the process of designing a virtual resistance system to simulate the behavior of tires in various conditions, a DC motor is used to create a simulated load. A load cell sensor is used to measure the actual force. In [7], a virtual force simulation observer with a sliding mode controller is used to control the force feedback in improving the realism and reliability of the said steering simulator.

Balachandran and Gerdes [8] proposed a vehicle model simulation to design a realistic artificial steering feel. A steer-by-wire vehicle was performing a dynamic weave test to obtain experimental performance measurements. Steering feel data was used to verify the validity of the model simulation design technique proposed. Balachandran and Gerdes [9] proposed the technique using objective steering feel measures. The desired steering feel can be implemented as the baseline steering feel on a steer-by-wire vehicle.

Fankem et al., [10] found that the complex friction of the real system influences the system dynamics, the proposed steering rack force estimation algorithm uses a friction compensation to find a linear model description. Zhang et al., [11] proposed fusion estimation method of the steering feedback torque and verified with the HIL platform. The fusion method was based on Kalman filter that combines a dynamics-reconstruction method and disturbance observer-based method. The dynamics-reconstruction method was designed according to the vehicle dynamics and used as the prediction model of the Kalman filter.

There was the development of force feedback for many application for virtual system and enhance realistic. Wang et al., [12] presents the development and feedback force control of a safe, lightweight, yet powerful, and stable passive force feedback data glove (FFDG), utilizing a disc-type magnetorheological (MR) brake as the force feedback device. They illustrated of the mechanical design of the FFDG and presented precise feedback force control. The control effect of the two methods is evaluated and compared through simulations

Guo et al., [13] proposed a Vascular Interventional Surgical Robotic System based on Force-Visual feedback. They evaluated experiment with force sensor and force feedback, Experimental results showed the system has good performance of the force feedback and the synchronous motion between the master and slave. There is a 1.2mm and 2.5 degrees of position errors and 20mN force error in the synchronous motion between the master and slave.

Sekizuka et al., [14] studied force characteristics during the lever operation and verify the effectiveness of the lever reaction force design. They constructed a model to predict the perceived force from the muscle activity estimated based on the posture and reaction force during the lever operation. Based on a musculoskeletal simulation for the lever operation, perceived force could be estimated between 7.8% to 14.3% root mean square errors. The reaction force characteristics were studied in which the perceived force varied linearly with the lever angle.

In this research, the development of a driving simulator for virtual training consists of three main phase. First phase started with installing measuring devices to collect the force data exerted by the driver at the gas pedal, brake pedal, and handlebar of a M60A3 tank. The force and position of the gas pedal and brake pedal were the main results in this paper. The force data is the reference data for designing the virtual tank driving simulator. The Second phase, the mechanism of the main battle tank was studied and then the propulsion mechanism of each system was designed. The force feedback systems which include the integration of a servo motor and a force sensor were developed. The last phase, prototype force feedback tank driving system was built and applied with feedback control system. The control algorithm or control scheme was designed to mimic the realistic of the driving.

The virtual tank driving simulator was designed and fabricated. It consists of a rigid cockpit structure that is movable by wheels. The dimension and functions of the cockpit was designed match to the actual system. Vehicle dynamic model was implemented to the virtual driving simulator as vehicle system integration as Hardware-in-the-loop (HIL). There was a 3D-virtual driving program applied to the simulator. Three frontal displays showed 3-dimension graphical display of the front view of the tank. Two touch screen displays use for dashboard control of the driving mode. There was a vibration system to produce vibration during the virtual tank driving simulation was moving to give realistic sensation. All driving results send to the trainee's computer to track the driving performance. Force feedback system can mimic and match the data collected from the tank. The results of gas pedal and brake pedal were compared with the actual M60A3 tank which the errors are less than 3%.

2. Experimental Setup

In order to capture driver feels from a M60A3 tank, the force information at three main components was measured and recorded. Those were a brake pedal, a gas pedal, and a handlebar that a driver interacted with. Fig. 1 showed the cockpit of a M60A3 tank that was installed force sensors at each component. Fig. 2a showed the brake pedal which installed a strain-gauge-type force sensing plate at front, and a laser-type position sensor at back. Maximum capacity of force measurement at a handlebar, a gas pedal, and a brake pedal were 100 N., 200 N., and 500 N. respectively. Laser Finder GP2Y0A21YK sensors were a position feedback for all three components.

The measurement system sent data to a real-time controller, and recorded information into time-series data as shown in Fig. 2b. The relationship of force and position of each component were analyzed and use as force reference for driver's feels.

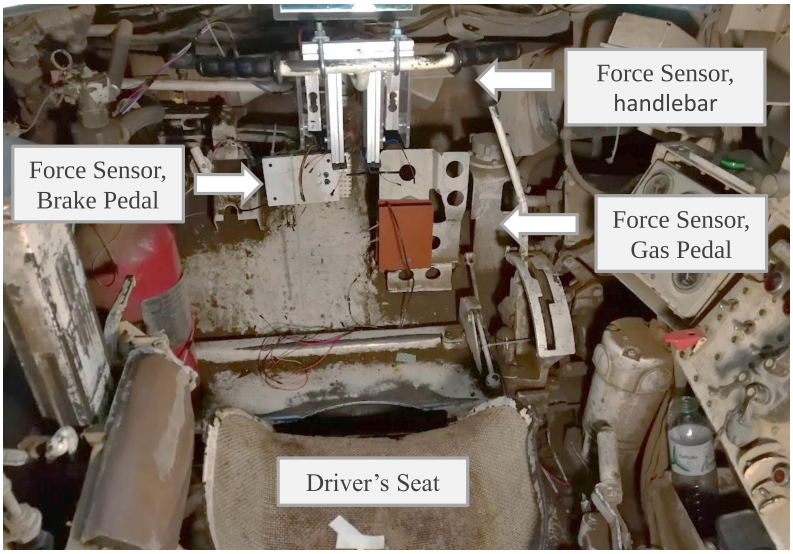


Fig. 1. Sensor installation in the cockpit of M60A3 tank.

(a) (b)

Fig. 2. (a) Force sensor installation at the brake pedal with a signal conditioning module.
(b) A real-time controller for data acquisition.

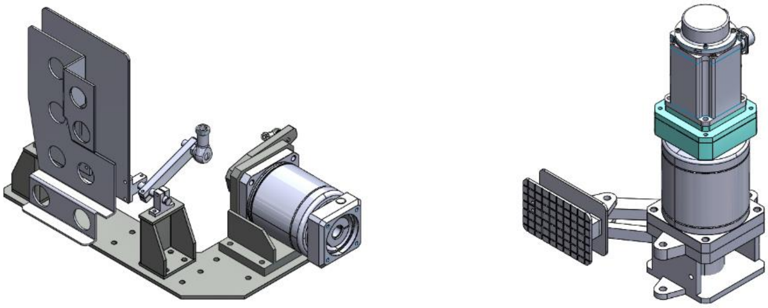
3. Design and Prototype a Virtual Tank Driving Simulator

The components in the cockpit of a M60A3 tank were designed based on the actual dimension to prototype the actual size tank driving simulator. Those main driving components (a brake pedal, a gas pedal, and a handlebar) were redesigned to force feedback systems by attaching geared AC servo motors coupling with the rotating joint of each mechanism. A strain-gauge-type force sensing plate installed in front of the both pedals, and both side of the handlebar.

Fig. 3a showed the gas pedal connected to a two-bar linkage and connect to the force feedback transmission system. The brake linkage (r_p) is 0.135 m. Maximum force at a gas pedal (F_p) was 200 N. The required torque $(\tau_p = F_p \times r_p)$ should be 27 N.m. In actuator selection, Sanyo Denki AC servo motor 0.75 kW with brake with RS3 amplifier 30 amp and a precision planetary gearbox with ratio of 30 were chosen. With 90% efficiency; the system can generate torque up to 64.26 N.m. or 2.4 times of the actual system.

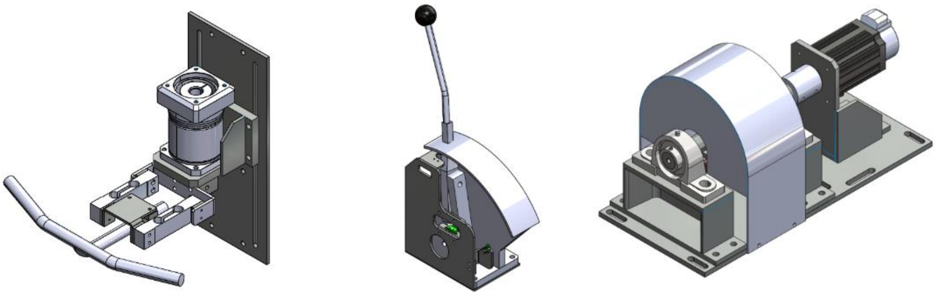
Fig. 3b showed the brake pedal connected to the four bar linkage mechanism and connected to the rotating axis which engaged to transmission system and the actuator. The brake linkage (r_b) is 0.19 m. Maximum force at brake pedal (F_b) was 500 N. The required torque $(\tau_b = F_b \times r_b)$ should be 95 N.m. In actuator selection, Sanyo Denki AC servo motor 1.2 kW with brake with RS3 amplifier 50 amp and a precision planetary gearbox with ratio of 40 were chosen. With 90% efficiency; the system can generate torque up to 205.2 N.m. or 2.2 times of the actual system.

Fig. 4a showed the handlebar connected to the force feedback transmission system directly which the required torque is 10 N.m. the 0.75 kW AC servo motor with a precision planetary gearbox with ratio of 15 is capable for 32.13 N.m. or 3.2 times for the actual system. Fig. 4b is a gear lever with position sensors to indicate four different modes of the driving such as "P", "R", "L", and "H" gear mode. Fig. 4c is the vibration generating system using an unbalance mass connected to a rotating shaft of another AC servo motor which the speed or the required torque can be controlled.



(a) (b)

Fig. 3. (a) The gas pedal with force feedback system. (b) The brake pedal with force feedback system.

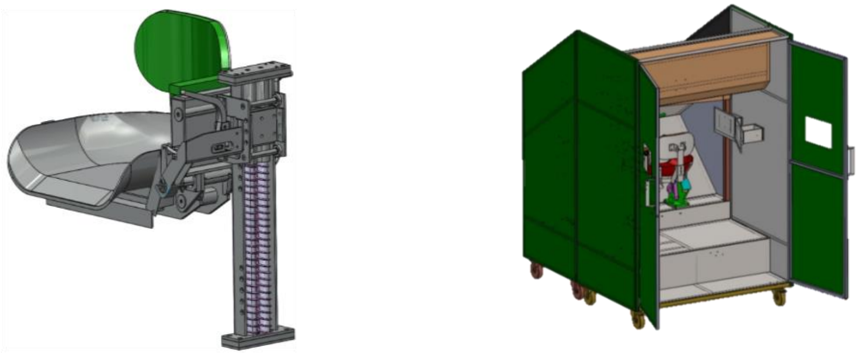


(a) (b) (c)

Fig. 4. (a) Handlebar with force feedback. (b) Gear lever with sensors. (c) Vibration generating system.

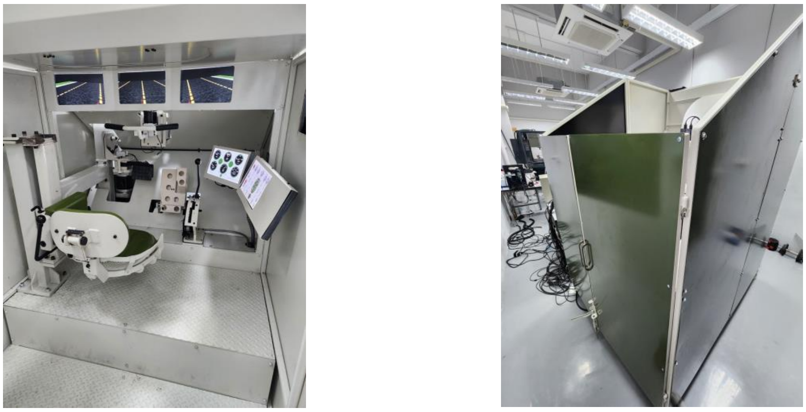
Fig. 5a showed the driver's seat which has the dimensions and functions similar to the actual seat. The first function is lifting up and down the seat with automatic lock mechanism. The 2nd function is sliding the seat forward and backward, and the 3rd function is to fold the seat. Fig. 5b showed the virtual tank driving simulator which contain all main components such as driving mechanisms, seat, control panels and displays at front. It is a portable cockpit with six free wheels attached at the bottom of the platform.

Fig. 6a showed the view inside the cockpit with all components. The simulator was installed the brake pedal, the gas pedal, the handlebar with force feedback systems as well as the driver's seat, gear lever, and control panels. Fig. 6b showed the front view of the virtual tank driving simulator which has the vibration generating system installed inside.



(a) (b)

Fig. 5. (a) Driver's seat (b) The design of virtual tank driving simulator.



(a) (b)

Fig. 6. Virtual tank driving simulator. (a) Inside view (b) Front view.

4. Force Feedback Control System

The tank's driving mechanisms with force feedback systems are a gas pedal ($i = 1$), a brake pedal ($i = 2$) , and a handlebar ($i = 3$) . The force and feedback positions were used as feedback signals to control industrial servo motors to generate resistance forces as the original M60A3 tank. The resistance force $\left(F_{r,i}\right)$ can be calculated from $F_{r,i} = \tau_{d,i}/r_i$ while the resistance torque $\left(\tau_{d,i}\right)$ is calculated by the Eq. (1) as:

$$\tau_{d,i} = \tau_{motor,i} + J_i\ddot{\theta}_i + b_i\dot{\theta}_i, \text{ where } i = 1, 2, 3 \tag{1}$$

$\tau_{motor,i}$ is the force feedback motor toque. J_i, b_i are the system inertia and system damping. θ_i is the rotating position of each joint mechanism which was sensed by absolute encoders mounted on the AC servo motors. Each position was the input of a control system to generate required motor toque. The force feedback of the each system was a proportional control with $K_{p,1} = 0.35$. $K_{p,2} = 0.085$ and $K_{p,3} = 0.15$ which were chosen to match the output range of the operation. Force sensors in Fig. 7a were calibrated and applied. The sensors and actuators connected real-time controller and FPGA were designed for the force feedback control as shown in Fig. 7b. The computer system showed all results to the trainee (Fig. 7c).

The posture of the tank was found by (x, y) position in the earth coordinate system and ϕ (orientation angle) is the angle between velocity vector (v_x) and axis x. The kinematic model of the tank can be written in Eq. (2) and Eq. (3).

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} \cos\phi & 0 \\ \sin\phi & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{2}$$

$$v = (v_R + v_L)/2,\ \omega = (v_R - v_L)/t \tag{3}$$

Velocity and angular velocity of the tank are v and ω. Velocities and angular velocities of the left and right wheels are $\omega_L = v_L r$ and $\omega_R = v_R r$. r is wheel radius. t is track width. The dynamic model of the tank can be written in Eq. (4) and Eq. (5).

$$m dv/dt = F_T - mg\sin\theta - \rho A C_d v^2/2 - R_t \tag{4}$$

$$J d\omega/dt = M_T - M_R \tag{5}$$

R_t is total resistance force. Aerodynamic drag and gravity resistance are presented in the Eq. (4). Traction force (F_T) is determined by left and right track traction forces (F_L, F_R); $F_T = F_L + F_R$. M_T is rotational torque; $M_T = (F_R - F_L)t/2$. M_R is moment resistance forces.

(a) (b) (c)

Fig. 7. (a) Force sensor. (b) Control cabinet. (c) Computer control system.

The kinematic model and the dynamic model of the tank were put into the computer software and use to present the realistic motion of the tank. Three frontal displays showed 3-dimension graphical display of the front view of the tank as shown in Fig. 8a. Two touch screen displays use for dashboard control of the tank as shown in Fig. 8b.

(a) (b)

Fig. 8. (a) 3-dimension graphical display (b) Dashboard control.

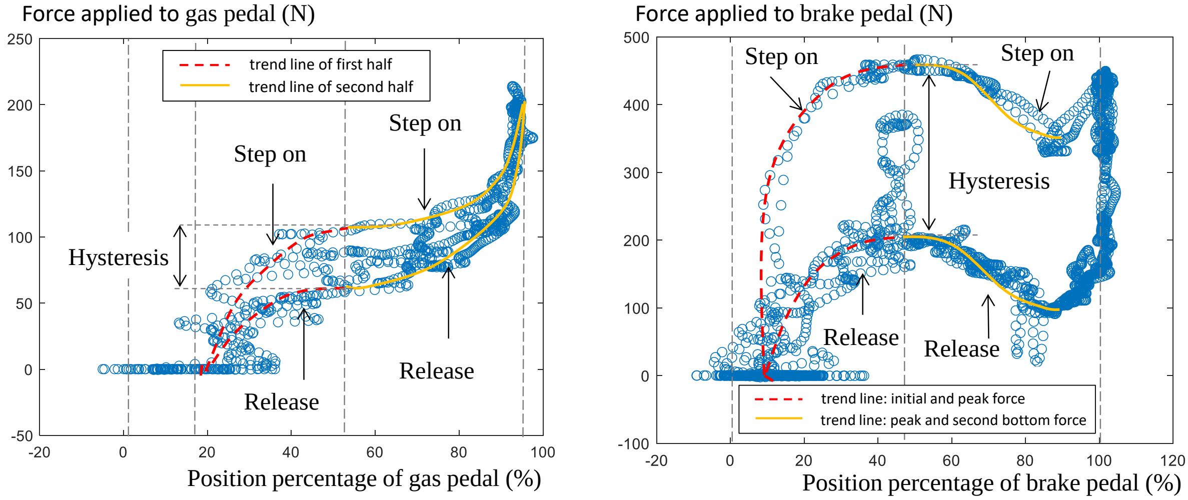
5. Experimental Results

5.1 Force and Frictions of M60A3 Tank

In the tests of the force applied to the brake pedal, gas pedal, and handlebar of the tank, signals from laser-type position sensors and strain-gauge-type force sensing plates were captured. Position data of each component was converted from voltage to position percentage range 0 to 100%.

From the experiments with the M60A3 tank, relationship of force applied to the gas pedal and the percentage of the gas pedal is presented in Fig. 9a. The results show the behaviors of the force friction when stepping on and releasing the brake pedal. The red dashed line presents the trend line of first half; the solid yellow line presents the trend line of second half of the gas pedal position. The friction of the gas pedal system is a nonlinear function as the relationship of position and force. The maximum force that driver had to press at the pedal was 214.06 N. The step on action required more effort than the release action. When the driver release the pedal, the force on pedal has different value as shown by the yellow trend line and red dashed line respectively as in Fig. 9a.The hysteresis value of the force was around 53 N.

Relationship of force applied to the brake pedal and the percentage of the brake lever, based on the tested on the actual tank, was shown in Fig. 9b. The results showed the huge different behavior of force friction when stepping on and releasing the brake pedal. The brake pedal characteristic is more complex than the gas pedal due to the hydraulic system of the braking system is huge and an old fashioned machine. The step on action required more effort than the release action. The maximum force of 466.78 N., the driver need to apply, was around half of the pedal position. The red dashed line presents the trend line between initial position and peak force position. When the driver step on the pedal from the middle position, there was the decreased of force which is showed by the yellow trend line from peak position and second bottom force position. After the second bottom force position, the driver need more effort to step on the pedal. When the driver released the pedal, there was hysteresis value of the force of around 250 N and the behavior of the force acting on the pedal is shown by the yellow trend line and red dashed line respectively as in Fig. 9b.



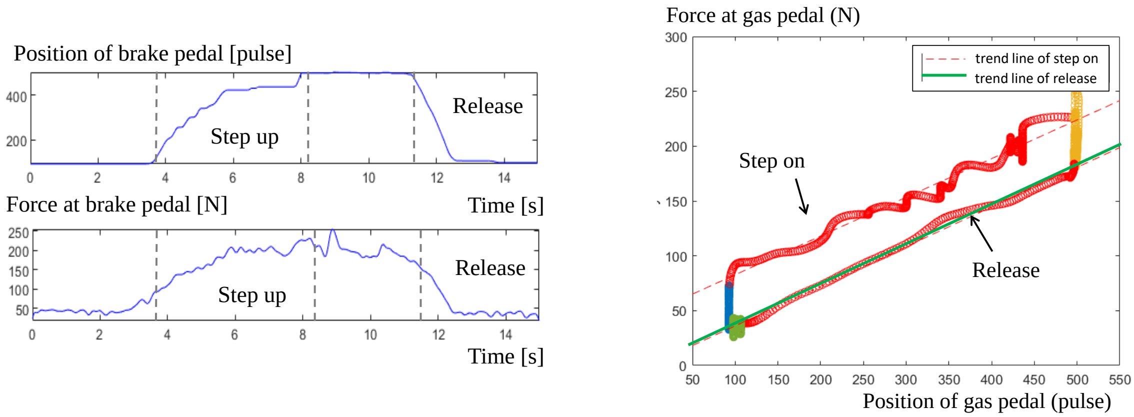
(a) (b)

Fig. 9. Relationship of force and position of (a) gas pedal, of (b) brake pedal of M60A3 tank.

5.2 Force Feedback Control of Virtual Tank Driving Simulator

The force feedback control system of the gas pedal and the brake pedal of the virtual tank driving simulator were tested by the driver by stepping on the pedal and release the pedal. The force and position results were compared with the actual force and position from the actual M60A3 tank results. Fig. 10a and 10b shows the experimental results of the gas pedal. Fig. 10a (top) showed time series data of position which 100% pedal position referred to 500 pulse of position signal. Fig. 10a (bottom) shows the force data, which measured from a force sensor, when stepping up the gas pedal during 3.6 to 8.2 seconds, and releasing the pedal from during 11.3 to 14.5 seconds. The 220 N. of force is needed to reach the maximum pedal position. $F_{r,1} = 0.3958p_1 + 1.31$

Fig. 10b showed the relationship of the force and position pulse of the gas pedal. The step on phase showed in the upper line which is close to the upper trend line, shown by red dashed line, of linear equation of $F_{r,1} = 0.3406p_1 + 53.97$. The release phase showed in the lower trend line, shown by green solid line, which is close to the linear equation of $F_{r,1} = 0.3958p_1 + 1.31$. The hysteresis of the force feedback is 51 N.



(a) (b)

Fig. 10. (a) Results of the gas pedal of the virtual tank driving simulator.
(b) Relationship of force and position of the gas pedal of the virtual tank driving simulator.

Fig. 11a and 10b shows the experimental results of the brake pedal. Fig. 11a shows the experimental results of two cycles of stepping up and releasing of the brake pedal of the virtual tank driving simulator. The first cycle data was collected during 0 to 30 seconds; the second one was collected between 30 and 80 seconds. The 100% pedal position equals to 380 pulse of position signal. The maximum of force in the brake system is 470 N. of force applied to the pedal.

Fig. 11b shows the relationship of the force and position pulse of the brake pedal. The first cycle's data shows by red dots, and the second cycle's data shows by blue dots. The first cycle, the driver press the pedal to the maximum position limit as the 470 N required then release the brake to an initial position. The second cycle, the driver pressed the pedal gradually and keep the position constant at different positions. The results of two cycles show the similar behavior of the hysteresis of the force feedback which is around 200 N.

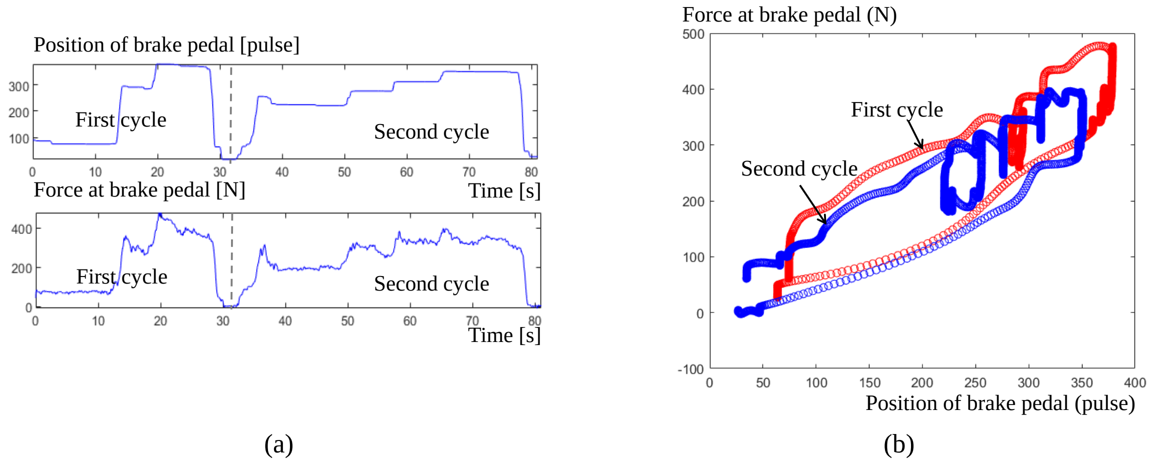


Fig. 11. (a) Results of the brake pedal of the virtual tank driving simulator.
(b) Relationship of force and position of the brake pedal of the virtual tank driving simulator.

6. Conclusion

From the experiments on the actual the M60A3 tank, the driver had to apply massive efforts on their feet to drive the old-flashed vehicle. The 214.06 N. and 466.78 N. of forces was the maximum payload to apply to the gas pedal and the brake pedal, respectively. There was hysteresis characteristic of force and position; those amount were around 53 N. and 250 N. on the gas pedal and the brake pedal, respectively.

The data from the actual tank was used for designing the virtual tank simulator with force feedback control system. From the experimental results, the responses of the force feedback control were fast and stabilize. There was hysteresis friction that the force feedback system can mimic the driving feeling of the M60A3 tank. With the proportional control system, the maximum of force in the brake system is 470 N. and the gas pedal is 220 N., respectively. However, there was a variation of data due to dynamic behaviour of the system. The experiments were conducted in low speed operation to compare the different between the force feedback control and the actual force from the tank was as following. In the gas pedal system, error of maximum force was 2.72%, error of maximum hysteresis error was -3.77%. In the brake system, error of maximum force was 0.69%, error of maximum hysteresis error was -20%. There were tests by tank drivers from Royal Thai Army; the human can feel the amplitude of force and time response generated by the control system match to the actual system. As their feedbacks, the force feel generated by the virtual force feedback system can generate the realistic feels to the virtual driving which can enhance the effectiveness of army personnel training. As to adjust the system, the feedback force can change easily with proportional control parameters. The further work is implementing gain-scheduling control, intelligent control, or nonlinear control which should improve the control performance.

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