ENHANCEMENTS OF ARMORED VEHICLE STABILITY USING ADAPTIVE CONTROLLER

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DEDICATIONS

To my beloved wife Anusiya Devi and our baby, my parents, parents-in-law, siblings and God

ABSTRACT

In the military vehicle application, it is a well-known fact that the armored vehicle will lost its directional stability once the armored vehicle is in lateral direction using large caliber gun while in a dynamic condition. This is because the gun recoil force acting at the center of weapon platform produces unwanted yaw moment at the body center of gravity of the armored vehicle. Recently, most of the military vehicles need to be in static condition during firing. Besides having reduced mobility, firing in static condition can cause the armored vehicle to be easily targeted for counterattack by the enemies. In order to overcome this problem, an active safety system namely Yaw Disturbance Rejection Control (YDRC) is proposed in this study. The proposed active safety system is used to improve the handling performance and maintain the directional stability of the vehicle by providing correctional steering angle to the Pitman arm steering mechanism. The steering correction is intended to reject the unwanted yaw motion and re-position back the armored vehicle back to its intended direction of travel path after firing. In this study, the proposed YDRC system is designed based on two outer loops namely Firing-On-the-Move (FOM) and Active Front Wheel Steering (AFWS). These outer loop control designs are developed to improve vehicle dynamic stability performance in terms of handling responses and directional path of the armored vehicle. The YDRC system is tested in both simulation and experimental studies using a prototype armored vehicle namely Half Scale SIBMAS. For simulation, YDRC system is tested on a validated 15 DOF armored vehicle via Software-in-the-Loop (SIL) simulation. Then, the performance of the YDRC system is enhanced using Neuro-PI controller by updating the Neural Network controller parameters based on back propagation gradient training algorithm. In order to evaluate the advantages of adaptive Neuro-PI controller experimentally, Hardware-in-the-Loop (HIL) simulation is performed using Pitman arm steering in prototype Half Scale SIBMAS using various testing criteria. Finally, the effectiveness of the proposed YDRC is evaluated on actual firing test via Real Implementation Test Scenario (RITS) using Half Scale SIBMAS based on critical firing condition. It can be noted that the lateral motion is improved up to 65% while the yaw response is improved almost 50% from conventional armored vehicle.

ABSTRAK

Dalam aplikasi kenderaan ketenteraan, diketahui bahawa kenderaan berperisai akan kehilangan kestabilan dinamik dan arah pemanduan ketika bergerak sambil menembak dengan menggunakan senjata berkaliber besar pada arah sisi. Ini disebabkan oleh impak yang terhasil daripada senjata dan menghasilkan gerakan rewang yang tidak diinginkan pada pusat graviti kenderaan berperisai. Oleh itu, kebanyakan kenderaan berperisai berada pada kedudukan statik semasa menembak. Walau bagaimanapun, keadaan ini menyebabkan kenderaan berperisai menjadi sasaran mudah serangan balas oleh musuh. Untuk mengatasi masalah ini, sistem keselamatan aktif iaitu pengawal penolakan gangguan rewang dicadangkan dalam kajian ini. Sistem ini digunakan untuk meningkatkan prestasi pengendalian dan mengekalkan arah pergerakan kenderaan berperisai ketika menembak dengan menghasilkan sudut kemudi yang bersesuaian menggunakan sistem kemudi *Pitman*. Pengawal sistem kemudi tersebut digunakan untuk mengurangkan pergerakan rewang yang tidak diingini dan mengembalikan semula kedudukan kenderaan berperisai ke hala tuju yang ditetapkan selepas tembakan. Dalam kajian ini, pengawal penolakan gangguan rewang yang dicadangkan telah direka berdasarkan dua reka bentuk kawalan luar iaitu penembakan ketika memandu dan sistem kemudi aktif roda hadapan. Reka bentuk kawalan luar lingkaran ini dibangunkan bagi meningkatkan prestasi kestabilan dinamik kenderaan tersebut dari segi prestasi pengendalian dan arah tuju laluan kenderaan. Sistem ini diuji secara simulasi dan ujikaji menggunakan kenderaan prototaip berskala separuh SIBMAS. Dalam ujian simulasi, sistem ini diuji menggunakan model 15-darjah kebebasan kenderaan berperisai yang telah disahkan secara gegelung-di-dalam-perisian. Seterusnya, prestasi sistem ini dipertingkatkan lagi dengan menggunakan pengawal *Neuro-PI* dimana parameter pada rangkaian *Neural* dikemaskini dengan menggunakan algorithma latihan-kecerunan-penyebaran-belakang. Untuk menilai kelebihan algorithma pengawal *Neuro-PI* secara ujikaji, gegelung-di-dalam-perkakasan dilaksanakan menggunakan sistem kemudi *Pitman* sebenar berdasarkan beberapa kriteria tembakan. Akhir sekali, keberkesanan algoritma yang dicadangkan diuji menggunakan kenderaan prototaip berskala separuh SIBMAS dalam keadaan tembakan kritikal. Hasilnya, prestasi gerakan pada arah sisi kenderaan berperisai dapat ditingkatkan sehingga 65% serta tindak-balas rewang telah meningkat hampir 50% berbanding dengan kenderaan berperisai tanpa sistem yang dicadangkan.

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APPROVAL

I certify that an Examination Committee has met on 9th April 2018 to conduct the final examination of Ahmad bin Abu on his degree thesis entitled 'Enhancements of Armored Vehicle Stability using Adaptive Controller'. The committee recommends that the student be awarded the Doctor of Philosophy (Mechanical Engineering).

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LIST OF ABBREVIATION AND SYMBOLS

CG	Center of Gravity
YDRC	Yaw Disturbance Rejection Control
HIL	Hardware – in – the – loop
SIL	Software – in – the – loop
RITS	Real – Implementation Test Scenario
FOM	Firing – On – the – Move
AFWS	Active Front Wheel Steering
DC	Direct Current
DOF	Degree of freedom
NI	National Instrument
MIL	Model – in – the – Loop
AFV	Armored fighting vehicle
HMMWV	High Mobility Multipurpose Wheeled Vehicle
MR	Magneto Rheological
RPG	Rocket Propelled Grenades
PD	Proportional Derivative
PID	Proportional Integral Derivative
ESC	Electronic stability control
ESP	Electronic stability program
ABS	Antilock Braking System
AYC	Active Yaw Control
EBD	Electronic Brake-Force Distribution
TCS	Traction Control System
ADRC	Active Disturbance Rejection Control
ESO	Extended State Observer
VILS	Vehicle – in – the – loop Simulation
DAQ	Data acquisition system
IMC	Integrated measurement and control
RMS	Root mean square
AIFS	Active Independent Front Steering
ECU	Electronic Control Unit
ADC	Analogue to Digital converter
RTWT	Real Time Windows Target
PTP	Peak-to-Peak
YDRC	Yaw Disturbance Rejection Control
GA	Genetic Algorithm
DOE	Design of experiment
ANOM	Analysis of mean
ANOVA	Analysis of variance
ITAE	Total of integral of time multiplied by absolute error
SNR	Signal-to-ratio

NN	Neural network
GUI	Graphic User Interface
GPS	Global Position Sensor
TCP/IP	Transmission Control Protocol/Internet Protocol
API	Application Program Interface
pvv	Process vector value
φ	Firing angle
F_{sfl}	Spring force at front left corner
F_{dfl}	Damper force at front left corner
F_{sfr}	Spring force at front right corner
F_{dfr}	Damper force at front right corner
F_{srl}	Spring force at rear left corner
F_{drl}	Damper force at rear left corner
F_{srr}	Spring force at rear right corner
F_{drr}	Damper force at rear right corner
F_{tfl}	Tire forces acting at front left of sprung mass
F_{tfr}	Tire forces acting at front right of sprung mass
F_{trl}	Tire forces acting at rear left of sprung mass
F_{trr}	Tire forces acting at rear right of sprung mass
$F_{z,fl}$	Front left tire normal force
$F_{z,fr}$	Front right tire normal force
$F_{z,rl}$	Rear left tire normal force
$F_{z,rr}$	Rear right tire normal force
$F_{x,fl}$	Longitudinal forces acting at front left tire
$F_{x,fr}$	Longitudinal forces acting at front right tire
$F_{x,rl}$	Longitudinal forces acting at rear left tire
$F_{x,rr}$	Longitudinal forces acting at rear right tire
$F_{y,fl}$	Lateral forces acting at front left tire
$F_{y,fr}$	Lateral forces acting at front right tire
$F_{y,rl}$	Lateral forces acting at rear left tire
$F_{y,rr}$	Lateral forces acting at rear right tire
$F_{y_{vss}}$	Estimated lateral force due to vehicle side slips change
F_{recoil}	Recoil force due to gun firing effect
F_y	Lateral force at CG of armored vehicle
R_{angle}	Gun recoil force due to varies firing angle
$M_{z,fl}$	Moment acting at front left tire
$M_{z,fr}$	Moment acting at front right tire
$M_{z,rl}$	Moment acting at rear left tire
$M_{z,rr}$	Moment acting at rear right tire
M_{fire}	estimated recoil moment acting at the CG of the vehicle system

M_{ideal}	Ideal moment required to reject recoil moment
M_{front}	Moment acting at the front vehicle body due to firing
M_{rear}	Moment acting at the rear vehicle body due to firing
M_{rotary}	Moment acting the CG of the vehicle due to firing
F_a	Aerodynamic force
F_r	Rolling resistance force
$F_{y_{summation}}$	Summation lateral force
$F_{sky_{front}}$	Skyhook force at front body
$F_{sky_{rear}}$	Skyhook force at front body
m	Net input to the layer
m_s	Sprung mass
$m_{u,fl}$	Front left unsprung mass
$m_{u,fr}$	Front right unsprung mass
$m_{u,rl}$	Rear left unsprung mass
$m_{u,rr}$	Rear right unsprung mass
m_m	Mass of projectile
m_w	Mass of propellant charge
m_i	ANOM value
m_{avg}	Average value of SNR
c_{fire}	Distance of center of gun system to CG of the body vehicle
β_g	Factor of activity gunpowder gases
C_d	Aerodynamic drag
C_r	Rolling resistance of tire
$\ddot{z}_s$	Acceleration of sprung mass at CG
$\dot{z}_s$	Sprung mass velocity at CG
z_s	Sprung mass displacement at CG
I_p	Pitch axis moment of inertia
I_r	Roll axis moment of inertia
I_z	Yaw axis moment of inertia
I_w	Wheel moment of inertia
$\ddot{\theta}$	Pitch acceleration at CG of sprung mass
$\dot{\theta}$	Pitch rate at CG of the sprung mass
$\ddot{\emptyset}$	Roll acceleration at C.G. of sprung mass
$\dot{\emptyset}$	Roll rate at C.G. of the sprung mass
w	Wheel base of sprung mass
h	Height from ground to the CG
h_{rc}	Height from ground to the center of roll angle
h_{pc}	Height from ground to the center of pitch angle
l_f	Distance between front of vehicle and CG of sprung mass

l_r	Distance between rear of vehicle and CG of the sprung mass
g	Gravitational force, 9.81 ms^{-2}
δ_f	Wheel steer angle
$K_{s,fl}$	Front left suspension spring stiffness
$K_{s,fr}$	Front right suspension spring stiffness
$K_{s,rl}$	Rear left suspension spring stiffness
$K_{s,rr}$	Rear right suspension spring stiffness
$C_{s,fl}$	Front left suspension damping
$C_{s,fr}$	Front right suspension damping
$C_{s,rl}$	Rear left suspension damping
$C_{s,rr}$	Rear right suspension damping
$z_{u,fl}$	Front left unsprung masses displacement
$z_{u,fr}$	Front right unsprung masses displacement
$z_{u,rl}$	Rear left unsprung masses displacement
$z_{u,rr}$	Rear right unsprung masses displacement
$\dot{z}_{u,fl}$	Front left unsprung masses velocity
$\dot{z}_{u,fr}$	Front right unsprung masses velocity
$\dot{z}_{u,rl}$	Rear left unsprung masses velocity
$\dot{z}_{u,rr}$	Rear right unsprung masses velocity
$\ddot{z}_{u,fl}$	Front left unsprung masses acceleration
$\ddot{z}_{u,fr}$	Front right unsprung masses acceleration
$\ddot{z}_{u,rl}$	Rear right unsprung masses acceleration
$\ddot{z}_{u,rr}$	Rear right unsprung masses acceleration
$z_{s,fl}$	Front left sprung mass displacement
$z_{s,fr}$	Front right sprung mass displacement
$z_{s,rl}$	Rear left sprung mass displacement
$z_{s,rr}$	Front right sprung mass displacement
γ_c	Camber angle
X	Slip angle (for lateral motion) or skid (for longitudinal motion)
B	Stiffness factor
C	Shape factor
D	Peak factor
E	Curvature factor
S_h	Horizontal shift
S_v	Vertical shift
a_x	Longitudinal acceleration
v_x	Longitudinal acceleration
a_y	Lateral acceleration
d_y	Lateral displacement
$\ddot{r}$	Yaw acceleration
$\dot{v}_x$	Inertial longitudinal acceleration

$\dot{v}_y$	Inertial lateral acceleration
$\dot{r}$	Yaw rate
r	Yaw angle
$\dot{r}_{dyn}$	Yaw rate after firing effect
$\dot{r}_{recoil}$	Unwanted yaw rate response which is caused by the recoil moment
a_{y_dyn}	Lateral acceleration after firing effect.
β	Vehicle body side slip angle
α_f	Lateral slip angle at the front tires
α_r	Lateral slip angle at the rear tires
λ_f	Longitudinal slip at the front tires
λ_r	Longitudinal slip at the rear tires
v_{wxf}	Longitudinal velocity at front tires
v_{wxr}	Longitudinal velocity at rear tires
v_o	Initial velocity of the projectile leaving the muzzle
$v_{y_{front}}$	Front vehicle lateral velocity
$v_{y_{rear}}$	Rear vehicle lateral velocities
$\dot{\omega}_{fl}$	Angular acceleration at front left tire
$\dot{\omega}_{fr}$	Angular acceleration at front right tire
$\dot{\omega}_{rl}$	Angular acceleration at rear left tire
$\dot{\omega}_{rr}$	Angular acceleration at rear right tire
$C_{f,f}$	Viscous friction coefficients at front tires
$C_{f,r}$	Viscous friction coefficients at rear tires
C_{sky_front}	Imaginary skyhook damper force at front body
C_{sky_rear}	Imaginary skyhook damper force at rear body
C_{sky_rot}	Imaginary skyhook damper force at CG body
C_{PID}	PID controller output
C_{PI}	PI controller output
k_p	Proportional gain
k_i	Integral gain
k_d	Derivative gain
Δk_p	Update for Proportional gain
Δk_i	Update for Integral gain
$e_i(t)$	error obtained due to the difference between desired and actual response of the system
K_{p_fire}	Proportional gain for FOM loop
K_{i_fire}	Integral gain for FOM loop
K_{p_yaw}	Proportional gain for AFWS loop
K_{i_yaw}	Integral gain for AFWS loop
R_w	Tire radius
y_a	Actual yaw rate response from neural network
y_m	Desired yaw rate response
$\propto_w$	Learning rate for weight