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Tactical Requirements Enforcing Ability Analysis of Different Weapon Manipulators for Military Unmanned Ground Vehicles

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ABSTRACT

It is an important work to design a weapon manipulator to satisfy the tactical needs for the military unmanned ground vehicles (MUGV). In this work, the RRR and 6-SPS mechanisms are proposed to design a weapon manipulator. The design factors for the weapon manipulator to satisfy the tactical needs are also discussed. According to the direct and inverse position analysis methods, the workspace analysis results show that these two mechanisms have better performances in satisfying the tactical needs than the RR and RPR mechanisms. The gradability performance is also discussed to verify that the proposed mechanisms can achieve a good performance. The analysis results can provide a reference resource for designers to design a weapon manipulator for MUGV.

Keywords: Military unmanned ground vehicles, MUGV, weapon manipulator, gradability performance

NOMENCLATURE

b_i	Vector from O_I to B_1
D	Vector from O_I to O_P
d_i	Vector from B_I to P_I
e_i	Unit vector of p_i^I
F_t	Tangent force of vehicle
F_n	Normal force of vehicle
h	Machine gun altitude
h_{P_s}	Altitude of position P_s
h_{Q_s}	Altitude of position Q_s
l_i	Length of i link
l_{max}	Maximum length of leg
l_{mim}	Minimum length of leg
N_p	Normal vector of the moving platform
P_i^p	Vector from O_P to P_I
Ps	Position vectors of muzzle
Qs	Position vectors of butt base
q_i	Vector from O_I to P_I
R_I^P	Rotation matrix
X_{Bi},Y_{Bi},Z_{Bi}	Leg frame i=1,2,3,4,5,6
X_I, Y_I, Z_I	Vehicle body frame
X_P, Y_P, Z_P	Moving platform frame
θ_c	Angle of $\angle OC_nR$
θ_r	Firing orientation angle
θ_p	Firing angle
θ_{tr}	Turn over angle
θ	Pitch angle
φ	Roll angle
ψ	Yaw angles

1. INTRODUCTION

At present, the short-range engagement in the combat for ground forces seems unavoidable. In order to reduce the casualties, the military unmanned ground vehicles (MUGVs) that install the offensive weapons are good programs for this purpose. The MUGV system is a small and lightweight unmanned ground vehicle that can perform dangerous patrol missions. Thus, the soldiers can avoid being exposed to danger. The most famous system of MUGV is the special weapons observation reconnaissance detection system (SWORDS)[1] that has been utilised as a standard equipment for the US Army. The US military evaluates that it will become the main ground force within decades. It will dramatically change the nature of war. Therefore, to cope with the future nature of war and reduce the casualties, the development of MUGV system will be crucial. For example, Israel has started to develop an unmanned security vehicles (USV)[2] system.

The basic need of the MUGV is that it should enforce the combat missions in different terrain features (Fig. 1) as a soldier does. In other words, the MUGV system should make use of different combat maneuvers in different terrain

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features to attack the enemies or take cover to protect itself from being harmed. Generally, a MUGV system consists of the vehicle, reconnaissance, navigation, armament, and fire control systems. The vehicle, reconnaissance and navigation systems can be called as the 'advance to contact' systems, and the armament and fire control systems can be called as the 'engagement systems'. The weapon manipulator is an important mechanism that connects the vehicle, armament and fire control systems, and also caries most of the payloads. An improper mechanism design leads to a poor combat maneuver which is unable to satisfy the tactical needs. Therefore, the mechanism, whether design is sufficient or not, will affect the performance of the MUGV system. For these reasons, it is important to design a weapon manipulator with higher performance for the MUGV to satisfy the tactical needs.

The scientific or technical literature of discussing the matter of weapon manipulators, which satisfy the tactical needs, are very rare upto now. In SWORDS, the weapon manipulator is an open loop chain robot that has two degrees of freedom (DOFs) and can be regarded as a RR mechanism[1]. The manipulator can operate the M249 machine gun with pitch angle (firing angle) about ± 22.5°. and azimuth (firing orientation angle) about ± 35°. The mechanism may only satisfy a portion of the tactical needs when it works in the complex terrain features, because the machine gun altitude will not able to be shifted. To further discuss the relationship between the weapon manipulator and the tactical needs, the factors for designing a weapon manipulator to satisfy the tactical needs are considered in this work. Furthermore, two types of weapon manipulators designed by the serial robot, such as RRR mechanism, and parallel robot, such as 6-SPS mechanism, are also proposed in this work. Based on the workspace analysis, the characteristics of serial (such as RR, RPR, RRR mechanisms) and parallel (such as 6-SPS) manipulator mechanisms are discussed. The analysis results of the workspace and tactical needs indicate that the RRR and 6-SPS mechanisms can be efficient design tactics for the weapon manipulator. The analysis results can be provided as a reference resource for the designer to design a weapon manipulator for the MUGV.

2. TACTICAL REQUIREMENTS ENFORCING ABILITY

In order to design a weapon manipulator for MUGV system to enforce combat mission in different terrain features as a soldier does, the firing postures utilised by soldiers in different terrain features (Fig. 1) have to be understood. Besides, in order to guarantee the equipment security, the attacking opportunity from enemy should be reduced. Generally, firing postures utilised by soldiers in battlefield are standing, kneeling and prostrating. Besides, they also have to march on different gradients of ramps, shoot at different altitude targets, and take cover behind the different altitudes of barriers. In addition, soldiers need to fire at obstacle flank when the obstacle is unable to be surmounted. Thus, for a MUGV system, the ability to operate a weapon with different firing postures like a soldier is needed.

Synthesising above explanation, there are four basic tactical requirements enforcing abilities (TREAs) that a weapon manipulator should have. These are: (a) shifting of gun altitude, that is, the system can take cover behind the different altitudes of obstacles and shoot the enemy, (b) adjustment of firing angle, that is, the system has the ability to shoot different altitude targets, (c) changing of the centre of mass of the whole system, so that a good operating or driving stability can be achieved when MUGV system is operated on different gradients of ramps, and (d) adjustment of the firing position to right or left, that is, MUGV system can take cover behind obstacles and fire at obstacle flanks.

The first three of the four TREAs are more critical, and can be treated as 'precondition ability' to satisfy the basic tactical needs. The fourth TREA leads to reduction of the vehicle exposed area in the enemy fire, i.e, the attacking opportunity from the enemy can be reduced. This ability can be treated as auxiliary ability. For these reasons, a designer who wants to design a weapon manipulator, first of all has to satisfy the basic tactical needs, i.e, the precondition ability as the top priority. A superior design is that which can satisfy four TREAs.

3. WEAPON MANIPULATOR DESIGN

The mechanisms of manipulators can be divided into serial, parallel, and hybrid types. The number of DOF are decided by the numbers of links, actuators, and joints. More number of DOF have greater capacity to enforce tactical needs. Generally, parallel type manipulator has good performance in stiffness and precision. However, the control problems may become more complex[3] than serial type. The serial type manipulator has wider workspace that leads to a good performance of TREAs and easier for trajectory planning than parallel type. For serial type, the more number of links has more number of DOF, but the stiffness may be reduced. Thus, sufficient number of DOF for a weapon manipulator are needed to satisfy the precondition ability.

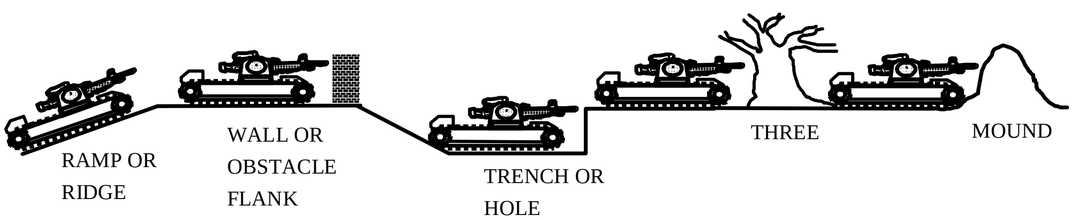


Figure 1. Typical terrain features diagram.

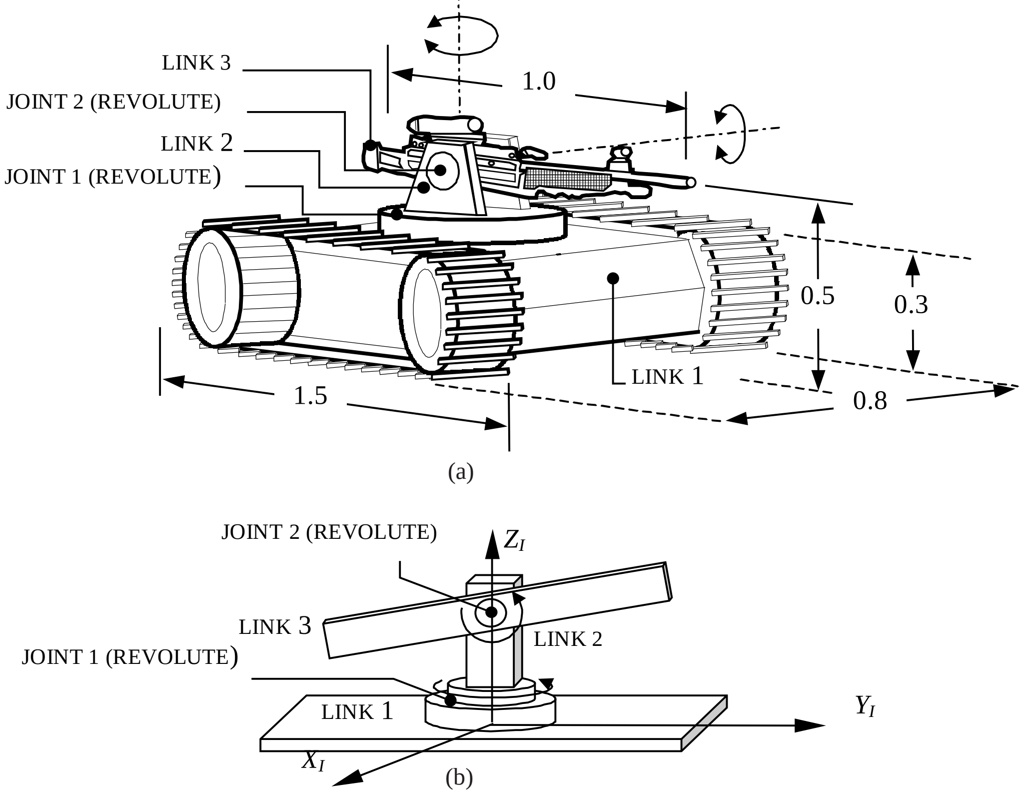


Figure 2. Configuration of RR mechanism: (a) sketch map; (b) mechanism configuration.

However, in order to achieve a good firing accuracy, sufficient stiffness is needed. That is, the factors of stiffness and numbers of DOF have to be considered at the same time when designing a weapon manipulator. In this work, the characteristics of the RR (SWORDS mechanism) and RPR mechanisms designed as a weapon manipulator are discussed. The performances of RRR and 6-SPS mechanism are analysed to find the advantages when utilising these two mechanisms to design a weapon manipulator.

In this work, the dimensionless length and mass are utilised for kinematics analysis. The length of machine gun and mass of vehicle are the references of length and mass, respectively. That is, the dimensionless length of machine gun and the dimensionless mass of vehicle are equal to 1.

3.1 RR and RPR Mechanism

The RR mechanism (Fig. 2) contains three links and two revolute joints. The manipulator operates the machine gun with 2-DOF. The machine gun altitude cannot be adjusted, thus, it is unable to shoot the targets that are sheltered by obstacle Fig. 3(a) and 3(b). Furthermore, the center of mass of the whole system cannot be changed, that it will lead to a poor gradability Figure 3(c). For these reasons, the mechanism only satisfies a portion of tactical needs.

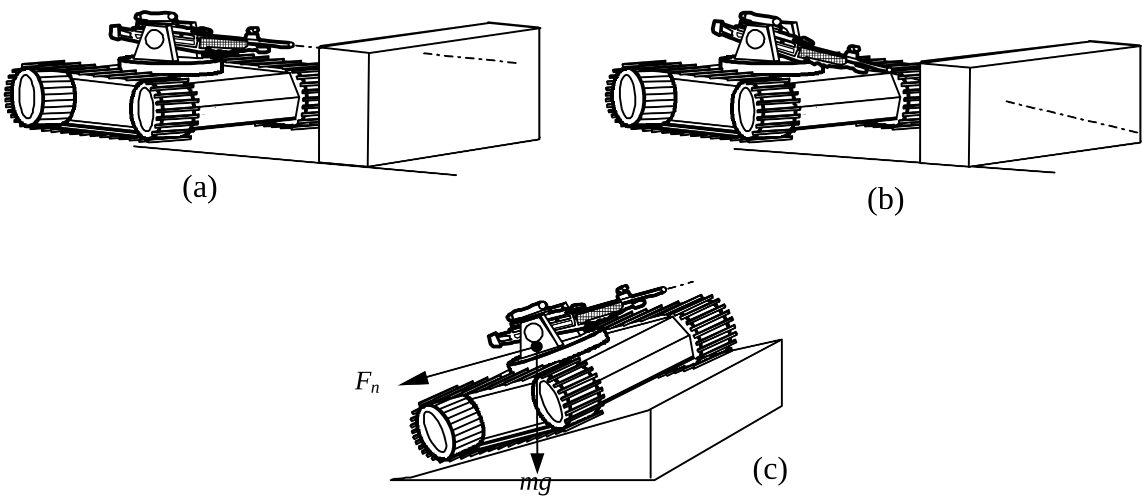


Figure 3. Restrictions of RR mechanism: (a) unable to surmount high obstacle and fire; (b) unable to shoot the target behind the high obstacle; and (c) poor gradability on different gradients of ramps.

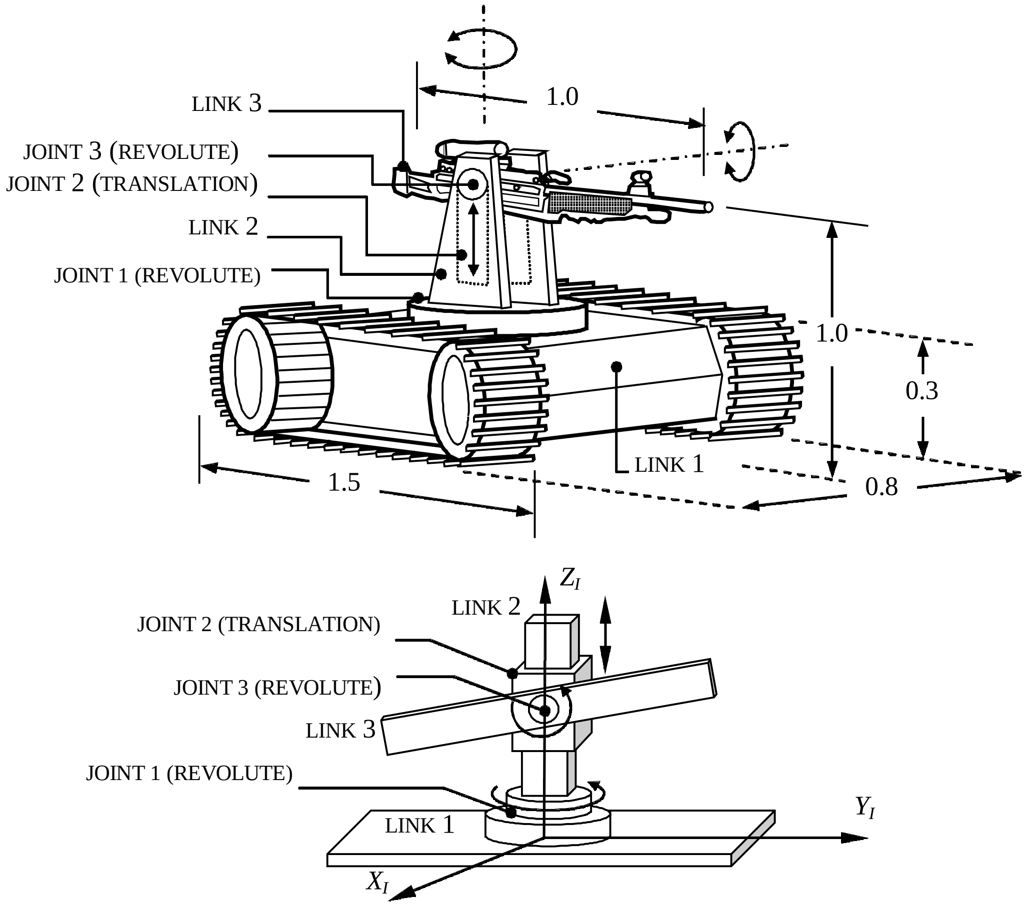


Figure 4. Configuration of RPR mechanism: (a) sketch map; and (b) mechanism configuration.

The RPR mechanism is similar to the RR mechanism but adds a translation joint in Link 2 (Fig. 4). The machine gun altitude can be adjusted, so that the machine gun can be operated with 3-DOF. Therefore, the disadvantage of the RR mechanism, that it is unable to adjust the gun altitude, can be solved. For this reason, the RRR mechanism can shoot the targets which are sheltered by obstacle Fig. 5(a) and 5(b). However, the centre of mass of the whole system also cannot be changed in forward and backward directions. It will lead to a poor gradability Fig. 5(c). Thus, the mechanism only satisfies a portion of tactical needs.

From above, it is observed that: (a) the RR mechanism can only satisfy the first TREA, and (b) the RPR mechanism

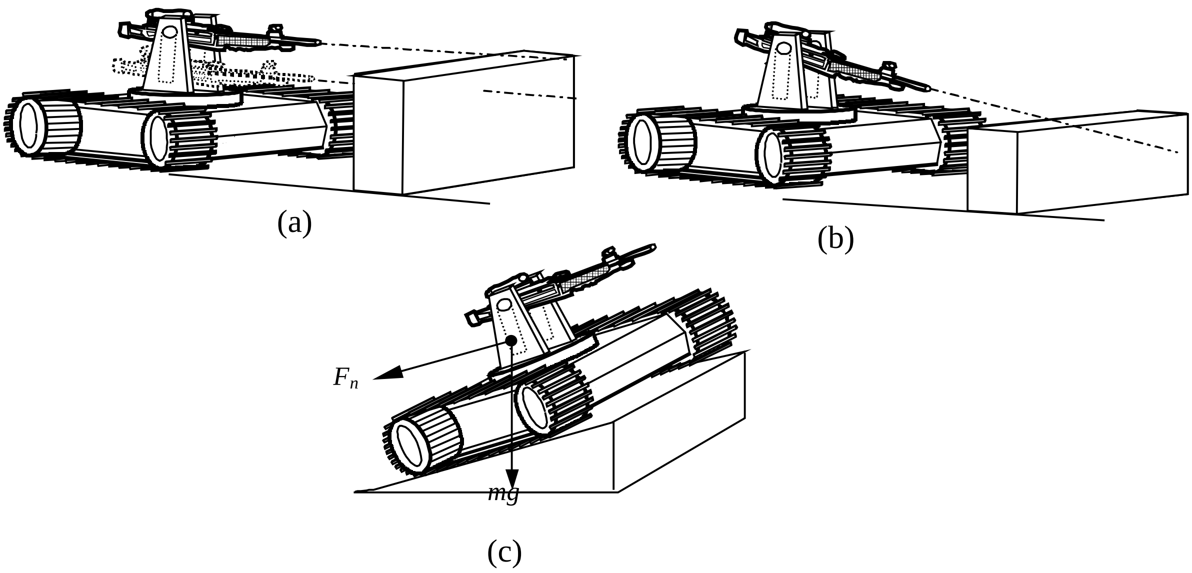


Figure 5. Restrictions of RPR mechanism (a) surmount high obstacle and fire; and (c) poor gradability at the different gradient of ramp.

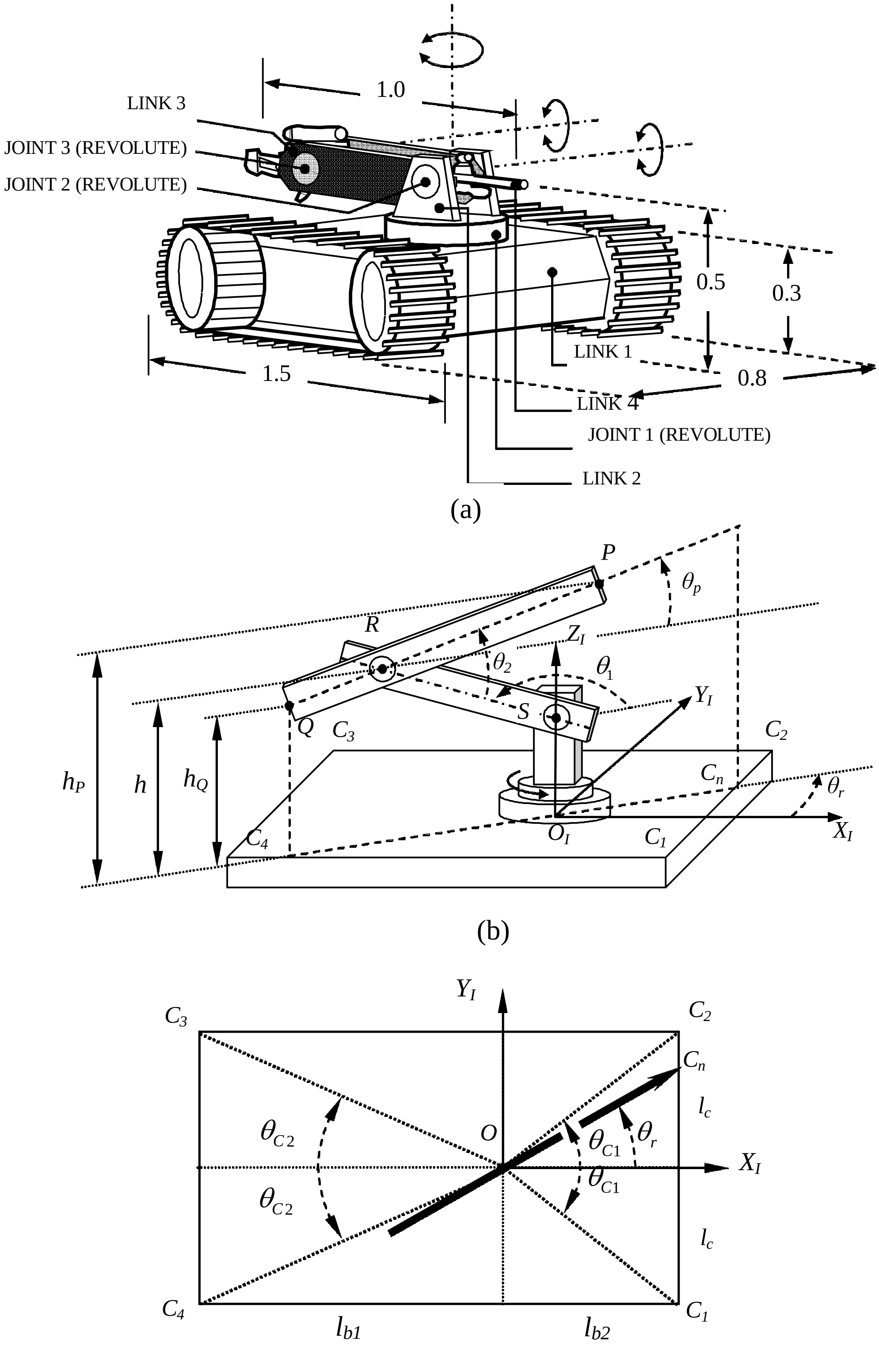


Figure 6. RRR mechanism: (a) sketch map; (b) mechanism configuration; and (c) top view.

can only satisfy the first and second TREA. In other words, these two mechanisms are unable to meet tactical needs completely. In order to design a mechanism that can meet the desired tactical needs, the RRR and 6-SPS mechanisms are examined here.

3.2 RRR Mechanism

This mechanism contains four links and three revolute joints Fig. 6 (a). The manipulator can operate the machine gun with different altitudes and firing angles by adjusting the angles of joint 2, (θ_2), and joint 3, (θ_2), Fig. 6(b). The machine gun also can be moved forward or backward. Thus, the machine gun can be operated with 4-DOF.

3.2.1 Workspace Analysis

The RRR mechanism is a serial type manipulator. The direct position analysis method is utilised for analysing the workspace. In Fig. 6(b), the mechanism is able to operate from the machine gun altitude *h*, firing orientation angle θ_r and firing angle θ_p by adjusting the angles of θ_r, θ_1 (angle of arm) and θ_2. Furthermore, the position vectors of *P*, *Q*, *R*, *S* and *O* are on the same plane. Let $\|\overline{OS}\| = l_1$, $\|\overline{SR}\| = l_2$, $\|\overline{RP}\| = \ell_4$ and $\|\overline{RQ}\| = l_4$, the firing angle θ_p and the position vector $P = [P_x \quad P_y \quad P_z]$, $Q = [Q_x \quad Q_y \quad Q_z]$ and $R = [R_X \quad R_Y \quad R_Z]$ can be represented in terms of θ_r, θ_1 and θ_2 as

$$\theta_p = \theta_2 - (\pi - \theta_1) \tag{1}$$

$$\begin{cases} R_x = l_2 \cos\theta_1 \cos\theta_r \\ R_y = l_2 \cos\theta_1 \sin\theta_r \\ R_z = l_1 + l_2 \sin\theta_1 \end{cases} \tag{2}$$

$$\begin{cases} P_x = (l_2 \cos\theta_1 + l_3 \cos\theta_p)\cos\theta_r \\ P_y = (l_2 \cos\theta_1 + l_3 \cos\theta_p)\sin\theta_r \\ P_z = l_1 + l_2 \sin\theta_1 + l_3 \sin\theta_p \end{cases} \tag{3}$$

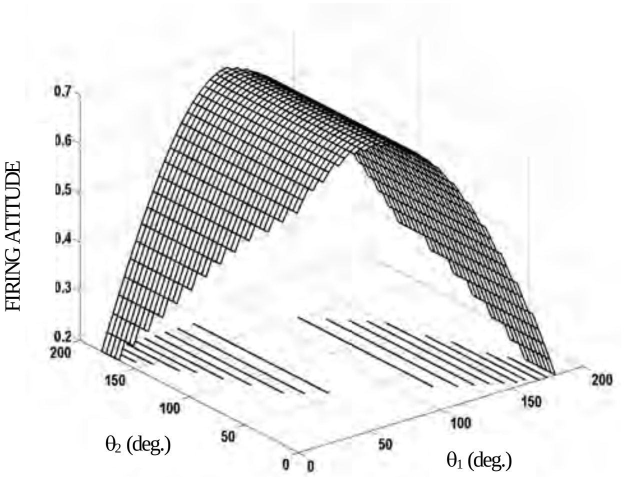
where machine gun altitude h=R_Z. From Eqns (2) and (3) to obtain the vector $\overline{RP} = [RP_x \quad RP_y \quad RP_z]$ can be obtained as

$$\begin{cases} RP_x = l_3 \cos\theta_p \cos\theta_r \\ RP_y = l_3 \cos\theta_p \sin\theta_r \\ RP_z = l_3 \sin\theta_p \end{cases} \tag{4}$$

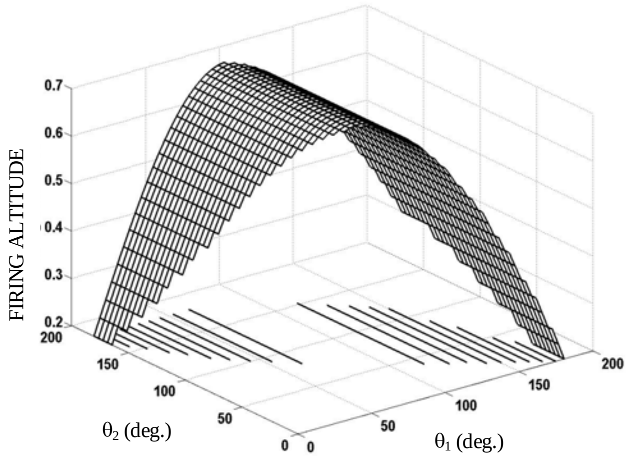
The vector $\overline{RQ} = -(l_4/l_3)\overline{RP}$, thus $\overline{RQ} = [RQ_x \quad RQ_y \quad RQ_z]$, can be obtained as

$$\begin{cases} RQ_x = -l_4 \cos\theta_p \cos\theta_r \\ RQ_y = -l_4 \cos\theta_p \sin\theta_r \\ RQ_z = -l_4 \sin\theta_p \end{cases} \tag{5}$$

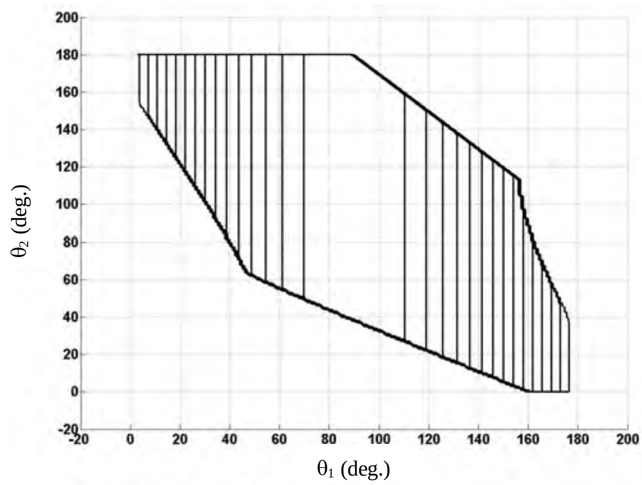
From Eqns (2) and (5) to obtain that position vector $Q = [Q_x \quad Q_y \quad Q_z]$ as



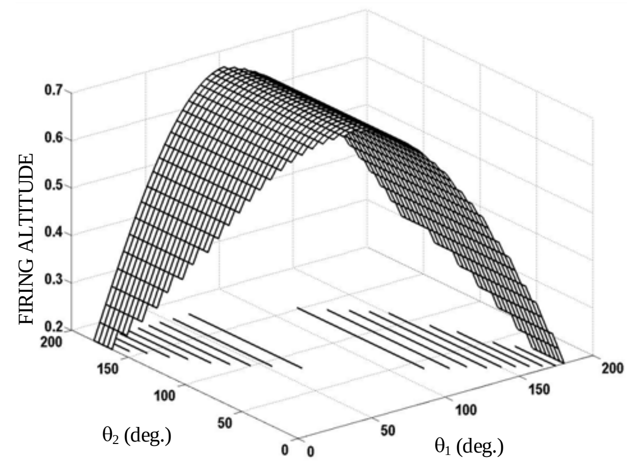
(a) 3-D workspace when θ_r=0.0°.



(c) 3-D workspace at θ_r = 157.2°.



(b) top view of contour Figure (a)



(d) top view of contour Figure (c)

Figure 7. Workspaces of firing altitude *h* with differen θ_1 and θ_2.

$$\begin{cases} Q_x = (l_2 \cos\theta_1 - l_4 \cos\theta_p)\cos\theta_r \\ Q_y = (l_2 \cos\theta_1 - l_4 \cos\theta_p)\sin\theta_r \\ Q_z = l_1 + l_2 \sin\theta_1 - l_4 \sin\theta_p \end{cases} \quad (6)$$

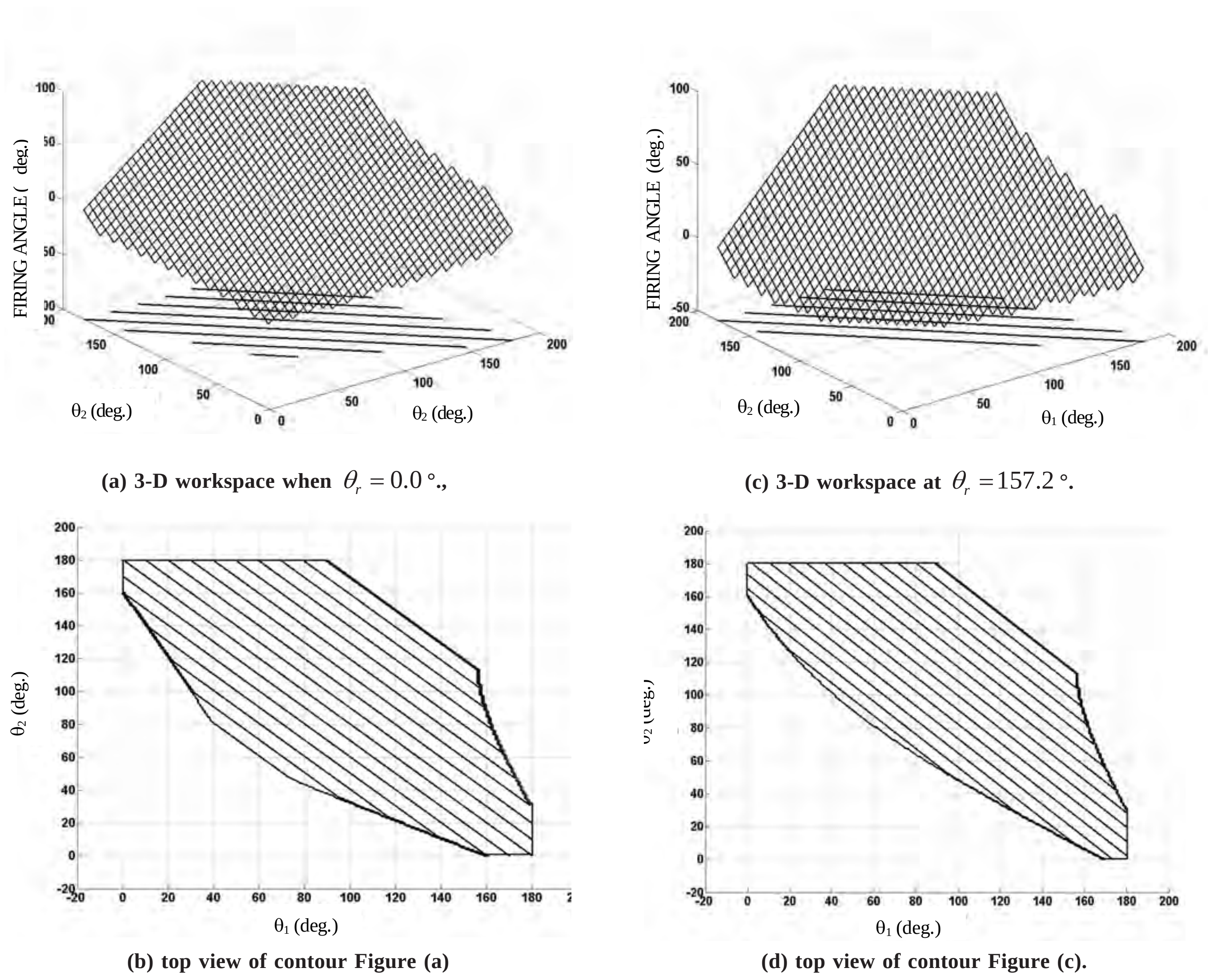
The constraint conditions for workspace analysis are assumed as: the altitudes of *P* and *Q* with respect to the vehicle body frame are $h_P > 0$ and $h_Q > 0$, the variation ranges of θ_1 and θ_2 are $0 \le \theta_1 \le \pi$ and $0 \le \theta_2 \le \pi$, respectively. In Fig. 6(b), it is evident that the vehicle body will be shot by the machine gun when the firing angle θ_p is smaller than the angle θ_c ($\angle OC_nR$). Thus, the firing angle θ_p should be constrained as $\theta_p \ge -\theta_c$. where

$$\theta_c = \cos^{-1}\left[\overline{RC_n} \cdot \overline{OC_n} \Big/ \left(\left|\overline{RC_n}\right|\left|\overline{OC_n}\right|\right)\right].$$

Assume the vehicle is a rectangular plane (Fig. 6 (c)). The position vector of C_n is given by

$$C_n = [C_{n,x} \quad C_{n,y} \quad C_{n,z}] = \begin{cases} C_{n,x} = l_{b2}, & C_{n,y} = l_{b2}\tan\theta_r, & C_{n,z} = 0, & -\theta_{c1} \le \theta_r \le \theta_{c1} \\ C_{n,x} = l_c \cot\theta_r, & C_{n,y} = l_c, & C_{n,z} = 0, & \theta_{c1} \le \theta_r \le \pi - \theta_{c2} \\ C_{n,x} = -l_{b1}, & C_{n,y} = -l_{b1}\tan\theta_r, & C_{n,z} = 0, & \pi - \theta_{c2} \le \theta_r \le \pi + \theta_{c2} \\ C_{n,x} = -l_c \cot\theta_r, & C_{n,y} = -l_c, & C_{n,z} = 0, & \pi + \theta_{c2} \le \theta_r \le 2\pi - \theta_{c1} \end{cases} \quad (7)$$

where $\theta_{c1} = \tan^{-1}(l_c/l_{b2})$ and $\theta_{c2} = \tan^{-1}(l_c/\ l_{b1})$. Assume the dimensionless length of each link as l_1=0.2, l_2=0.5, l_3=0.6, l_4=0.4, l_{b1}=0.95, l_{b2}=0.55 and l_c=0.4. At the different firing orientation angles (θ_r), the workspaces of firing altitude *h* and the firing angle θ_p versus to θ_1 and θ_2 are shown in Figs 7 and 8. In Fig. 7, the mesh surfaces indicate the workspaces of θ_1 and θ_2 versus *h*. Figure 7(a) shows that the *h* changes with θ_1, but the firing altitude variation ranges may be restricted by θ_2. The reason is that the different angles of θ_2 lead to different values of h_Q, h_P, and θ_p. The firing altitude will be restricted when $h_Q <$ 0, $h_P <$ 0 or $\theta_P < \theta_c$. For the same reasons, the variation



(a) 3-D workspace when $\theta_r = 0.0°$.,

(c) 3-D workspace at $\theta_r = 157.2°$.

(b) top view of contour Figure (a)

(d) top view of contour Figure (c).

Figure 8. Workspaces of firing angle *h* with different $\theta_1$and θ_2.

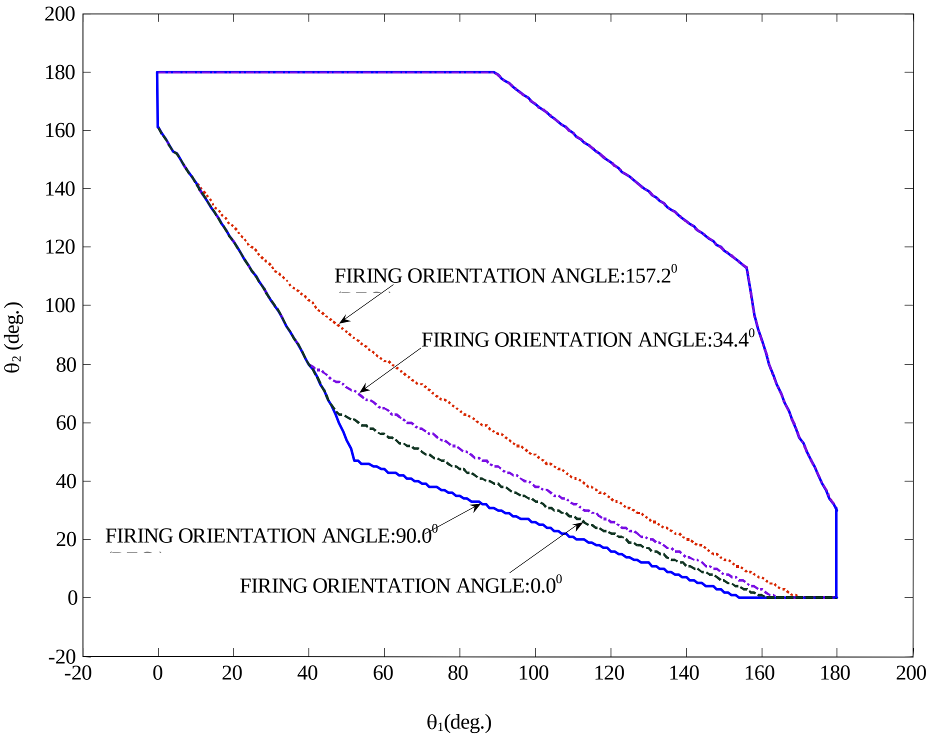


Figure 9. Workspaces of θ_1 and θ_2 with different firing orientation angles θ_r.

range of θ_2 is restricted by θ_1 and θ_r. Figures 7(b) and 7(d) show that θ_2 has the maximum variation range when θ_1 = 90 °.

In Fig. 8, the mesh surfaces indicate the workspaces of θ_1 and θ_2 versus the firing angle Q_p. Figures 8(a) and 8(c) show that the firing angle changes with θ_1 and θ_2. Furthermore, the machine gun has the maximum firing angle θ_p = 90° when $\theta_2 = 90 \sim 160°$ The minimum firing angle θ_r = –170° occurs at θ_1 = 50° and θ_p = 60°. By comparing Fig. 7(b) with Fig. 7(d) or Fig. 8(b) with Fig. 8(d), when the firing orientation angle θ_r turns to the direction of $\overrightarrow{OC_3}$ (θ_r = 157.2°), the variation range of θ_2 become smaller. The reason is that the longer length of $\overrightarrow{OC_3}$ leads to more restriction on the firing angle so that the vehicle is not shot by the machine gun. The workspaces of θ_1 *and* θ_2 with different firing orientation angles θ_r are shown in Fig. 9. The $\overrightarrow{OC_n}$ has the minimum length when θ_r = 90° , thus, θ_2 has the maximum variation range.

3.2.2 Gradability Analysis

In this work, the turn over angle θ_{tr} is the criterion for the gradability analysis. In Fig. 10, the turn over angle is defined as $F_t \times l_t > F_n \times l_n$ where F_t and F_n represent the longitudinal and normal forces of the vehicle with respect to the ramp angle, respectively. l_t and l_n represent the constant perpendicular distances from the pivot to longitudinal and normal forces, respectively. It is evident that the longitudinal force will increase and the normal force will decrease with increase in ramp angle, and the turn over occurs when the ramp angle becomes large enough and leads to $F_t \times l_t > F_n \times l_n$.

In previous section, the results of workspaces analysis reveal the machine gun altitude and position with respect to the vehicle body frame are changed with θ_1. In other words, the centre of mass (CM) of whole system also changes with θ_1. It is well-known that different location of CM will lead to the different performance of gradability. In this work, for RRR mechanism, assume the dimensionless mass of link 1 (vehicle) is 1, the link 2 is 0.01, link 3 is 0.1 and link 4 is 0.35. For RPR mechanism, assume the dimensionless masses of link 1 (vehicle) is 1, link 2 is 0.11 and link 3 is 0.35. In RPR mechanism, the dimensionless mass of link 2 is equal to dimensionless mass of link 2 plus link 3 of RRR mechanism. Furthermore, the vehicle and machine gun have the same mass for each mechanism. Let the CM be at the centre of each link. Based on these assumptions, RRR and RPR mechanisms have the same mass, so that the turn over angle (maximum gradient) of these two mechanisms with different firing altitudes and on different gradients of ramps can be compared.

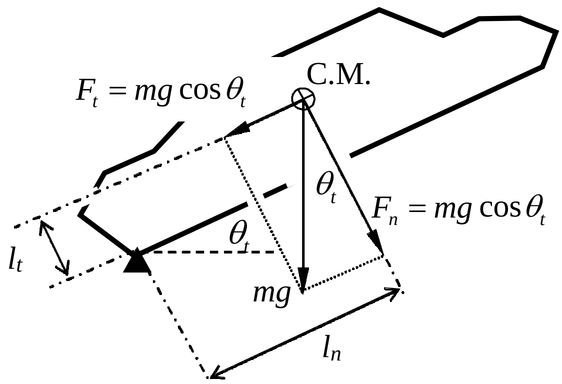


Figure 10. Turn over angle diagram.

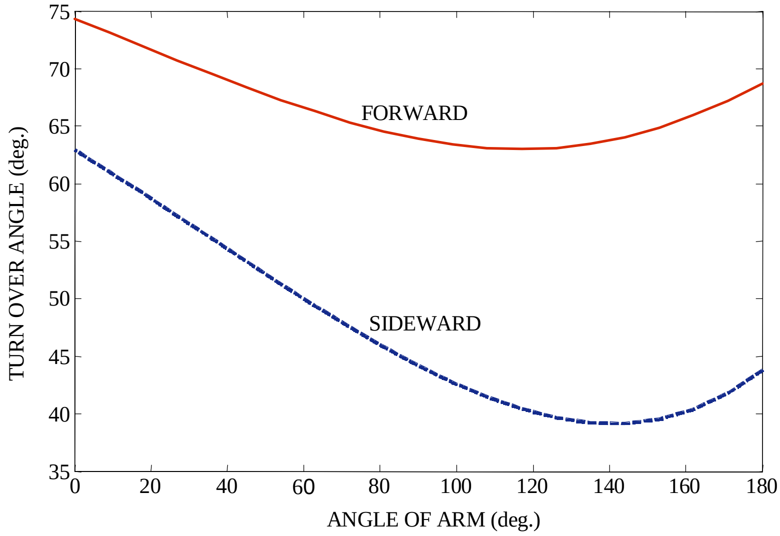


Figure 11. Turn over angles of RRR mechanism on forward and sideward ramp with different angles of arm θ_1.

For RRR mechanism, the highest firing altitude (gun altitude) occurs at $\theta_1 = 90^0$. The CM will be moved forward when $\theta_r = 0.0^0$ and $\theta_1 < 90^0$. The CM will be moved backward when $\theta_1 > 90^0$. For these reasons, the maximum turn over angle occurs at $\theta_1 = 0.0^0$. (Fig. 11) when the vehicle is on the forward ramp (Fig. 14(c)). Furthermore, for the same firing altitude, the turn over angle of RRR mechanism is greater than RPR mechanism when vehicle is on the forward ramp (Fig. 12) and on the sideward ramp (Fig. 13). Thus, the RRR mechanism has better gradability performance then RPR mechanism.

From above discussion, it is inferred that the RRR mechanism which is designed as a weapon manipulator has the following characteristics: (a) The machine gun altitude can be adjusted, that is, the MUGV system can take cover behind the different altitudes of obstacles and shoot the enemy (Figs 14(a) and 14(b)) and (b) the CM of the whole system can be changed, that it can achieve a good operating stability on the different gradients of ramps. (Fig. 14(c)).

For these reasons, the mechanism can satisfy widely tactical needs, that is, the MUGV system is suitable for more complex gradual terrain.

3.3 6-SPS Mechanism

The mechanism is called as the Stewart-Gough Platform, which was proposed in 1965 by Stewart[4]. The special in-parallel chains of a parallel manipulator have the advantages[5] as 6-DOF, highly precise positioning, and high load carrying capacity. For these reasons, Stewart-Gough Platform has been widely introduced in many industries. These applications include large-displacement driving simulator[6], active vibration control platform[7], precise positioning/fine-tuning[8], endoscope[9], and automatic painting machine[10], etc. In this work, the Stewart Platform is utilised to design a weapon manipulator for a MUGV system.

The configuration of the whole system (Fig. 15) shows that the machine gun and the moving platform can be treated as the same link, that is, the mobility of machine gun has 6-DOFs.

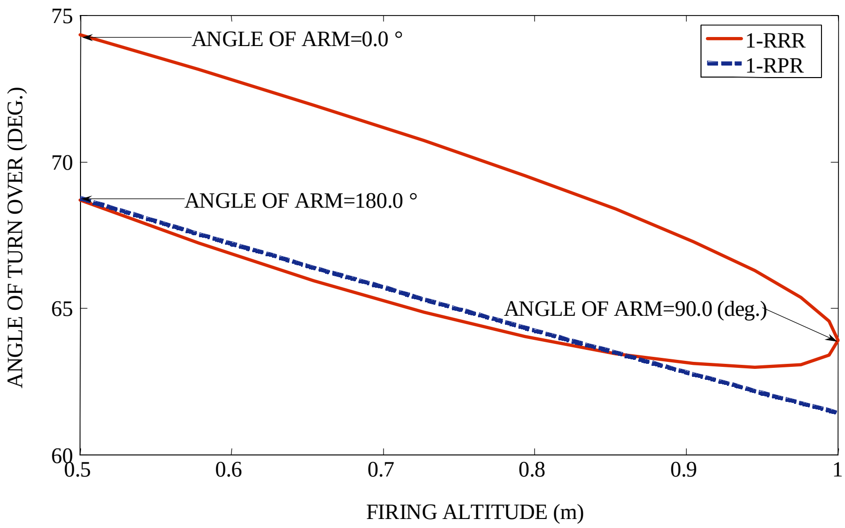


Figure 12. Turn over angles of RPR and RRR mechanism with different firing altitudes on forward ramp when $\theta_r = 0^o$.

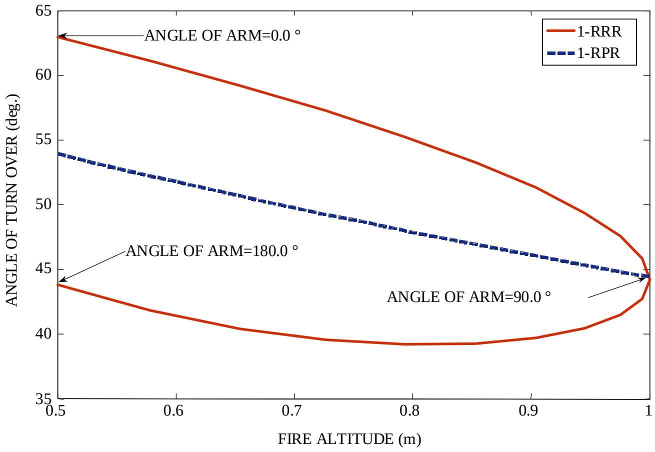


Figure 13. Turn over angle of RPR and RRR mechanism with different firing altitudes on right-sideward ramp when q_r = 270.00°.

3.3.1 *Workspace Analysis*

For a parallel manipulator, the inverse kinematics are straightforward, whereas direct kinematics are difficult to solve[11]. Thus, the inverse position analysis is utilised in this work. To represent the kinematic relations between the base platform, moving platform (machine gun) and six legs, three types of coordinate systems are defined. These are base platform frame (vehicle body frame or inertia frame X_I ,Y_I,Z_I), moving platform frame (X_p,Y_p,Z_p) and leg frame (X_{Bi},Y_{Bi},Z_{Bi}, i =1,2,3,4,5,6). The origins O_I, O_P, and O_{Bi} of these coordinate systems are located at the centre of base platform, moving platform and each leg of its spherical joints that connect to the base platform (Fig. 15(b)). For the vector representation, D is the vector from O_I (the origin of the inertial base frame) to O_P (the origin of the inertial moving frame); b_i is the vector from O_I to the i^{th} lower attachment point (revolute joint 2) B_i ; q_i is the vector from O_I to the i^{th} upper attachment point (sphreical joint) P_i ; d_i is the vector from B_i to P_i of the i^{th} leg; P_i^P is the vector from O_P of moving (platform) frame to P_i ; and P_i is P_i^P with respect to base (inertial) frame (Fig. 15 (b)).

The rotation representation of the inertial frame and moving frame are defined as follows: Rotation of an angle ψ about the inertial Z_I-direction, followed by a second rotation of an angle θ about the inertial Y_I direction, and then followed by a third rotation of an angle φ about the inertial X_I direction. This means that inertial frame will coincide with the moving frame through the rotation angles ψ, θ, and φ in sequence. Here the anglesψ, θ , and φ are the yaw, pitch, and roll angles, respectively. The resulting rotation matrix R_I^P is obtained by a post-multiplication of the three basic rotation matrices as follows:

$$R_I^P = R_x(\varphi)R_y(\theta)R_z(\psi) =$$
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c\varphi & s\varphi \\ 0 & -s\varphi & c\varphi \end{bmatrix}\begin{bmatrix} c\theta & 0 & -s\theta \\ 0 & 1 & 0 \\ s\theta & 0 & c\theta \end{bmatrix}\begin{bmatrix} c\psi & s\psi & 0 \\ -s\psi & c\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{8}$$

The position vector q_i of B_i with respect to the inertial coodinate system is obtained by the following transformation:

$$q_i = D + p_i^I \tag{9}$$

$$d_i = q_i - b_i \tag{10}$$

where $p_i^I = [R_I^P]^T p_i^P$, and the unit vector of p_i^I can be obtained as

$$e_i = \frac{[R_I^P]^T p_i^P}{\sqrt{\left([R_I^P]^T p_i^P\right)^T \left([R_I^P]^T p_i^P\right)}} \tag{11}$$

From Eqn (11), $\overline{O_pP_s} = \left\|\overline{O_pP_s}\right\| e_1$ and $\overline{O_pQ_s} = -\left\|\overline{O_pQ_s}\right\| e_1$.

Thus, the position vectors of muzzle P_s and butt base Q_s with respect to the vehicle frame are given by

$$P_s = [P_{s,x} \quad P_{s,y} \quad P_{s,z}] = \overline{O_pP_s} + D \tag{12}$$

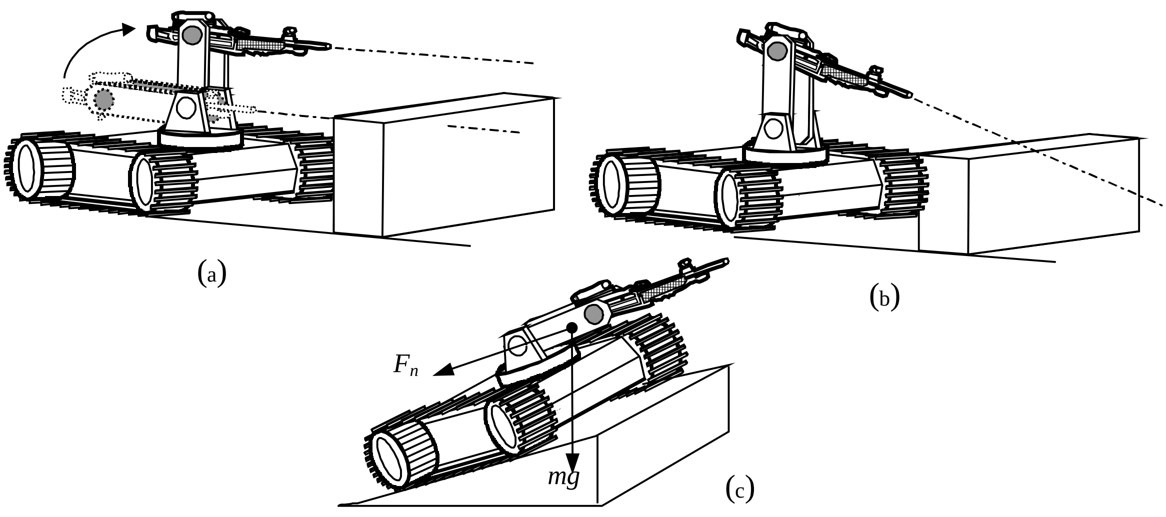


Figure 14. Abilities of RRR mechanism: (a) surmount the high obstacle and fire; (b) shoot the target behind high obstacle; and (c) changing the center of mass to forward to improve the stability.

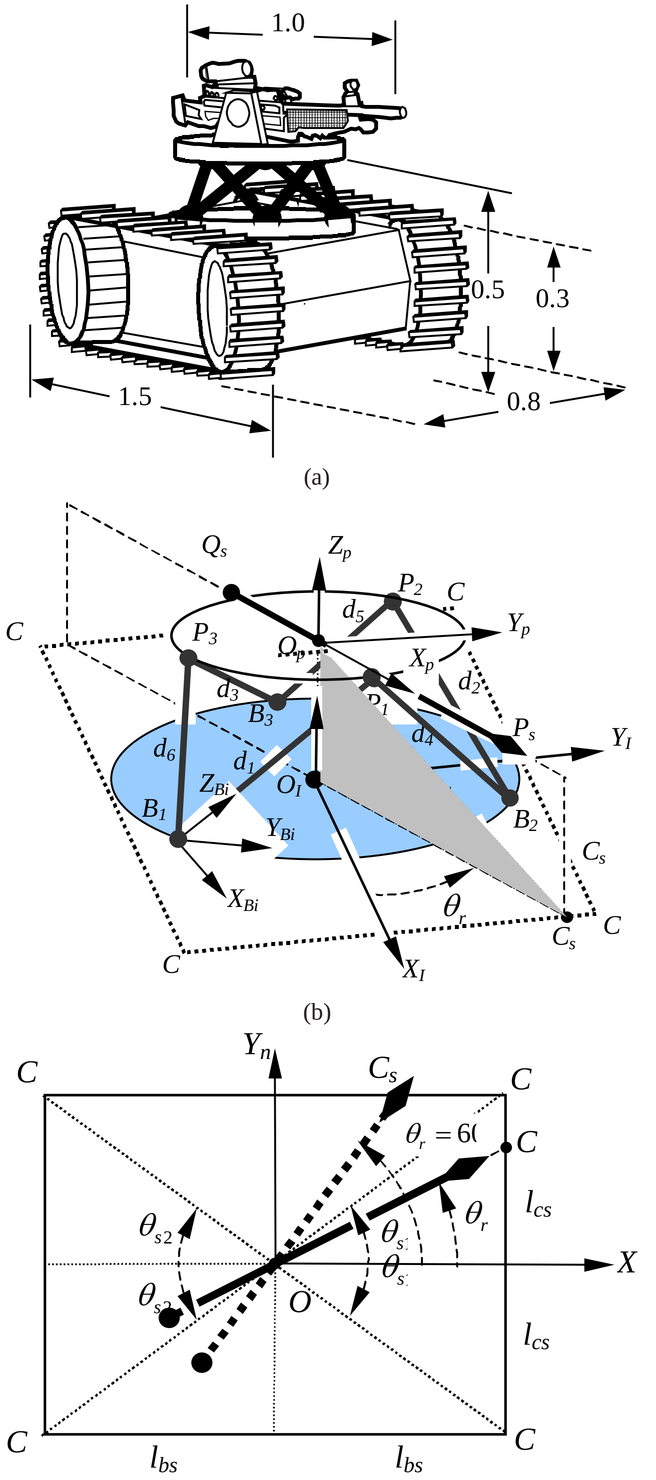


Figure 15. 6-SPS mechanism: (a) system configuration; (b) coordinate systems; and (c) top view.

$$Q_s = [Q_{s,x} \quad Q_{s,y} \quad Q_{s,z}] = \overline{O_p Q_s} + D \tag{13}$$

The altitude of P_s and Q_s relative to the vehicle are given by $h_{P_s} = \|P_{s,z}\|$, $h_{Q_s} = \|Q_{s,z}\|$. According to Eqn (10), the length d_i of the i^{th} leg is

$$d_i = \sqrt{(q_i - b_i)^T (q_i - b_i)} \tag{14}$$

Furthermore, substitution of Eqn (10) into Eqn (9) yields

$$d_i = D + [R_I^P]^T p_i^P - b_i \tag{15}$$

As derived, if the position and orientation of moving platform are given, the vectors and lengths of the six legs can be obtained by Eqns (14) and (15).

In this work, the constraint conditions for workspace analysis are the minimum and maximum length of each leg (l_{max}, l_{mim}, that is), singularity conditions $d_i = D + [R_I^P]^T p_i^P - b_i$ (N_p is the normal vector of the moving platform, and d_i is the vector of each leg.), the restrictions of the altitudes of h_{P_s} and h_{Q_s} ($h_{P_s} > 0$, $h_{Q_s} > 0$) and the firing angle θ_p (the same as RRR mechanism). Therefore, the constraint conditions in analysing the workspace differ from the traditional 6-SPS mechanism. Furthermore, the wider workspaces of surge (firing altitude), sway and pitch (firing angle) are the main performance parameters when utilising the 6-SPS mechanism as a weapon manipulator. Thus, the position workspace with constant orientation (PWO) and the orientation workspace

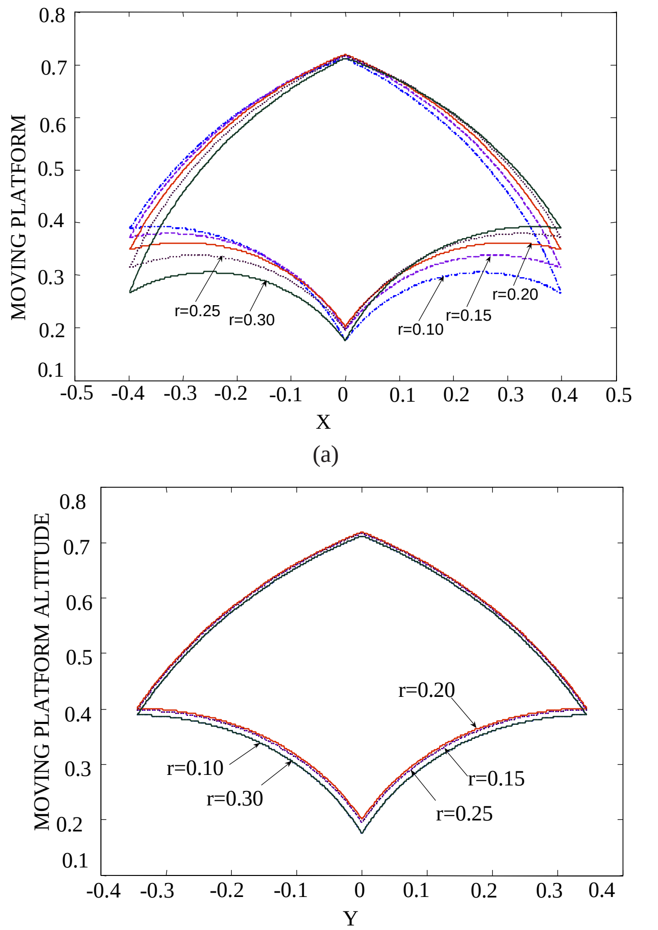


Figure 16. $\psi = 0, \theta = 0, \varphi = 0$ and x=0, the workspaces with different radii, r, (a) Surge versus heave and (b) Sway versus heave.

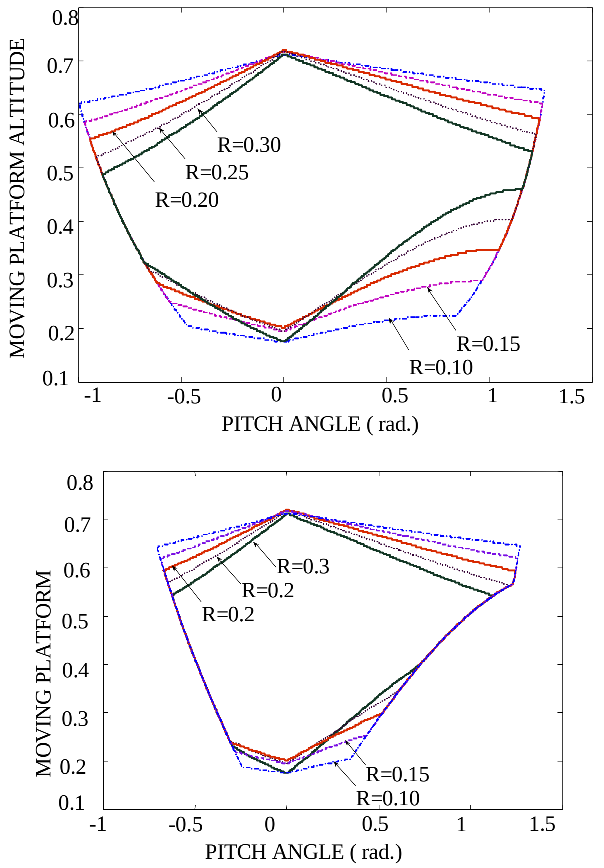


Figure 17. y=0, j=0, *x* = 0 and y = 0, the workspaces of Pitch versus Heave with different radii *r*, (a) don't consider constraints and (b) consider the constraints of h_{Ps} > 0, h_{Qs} > 0 and angle q_p.

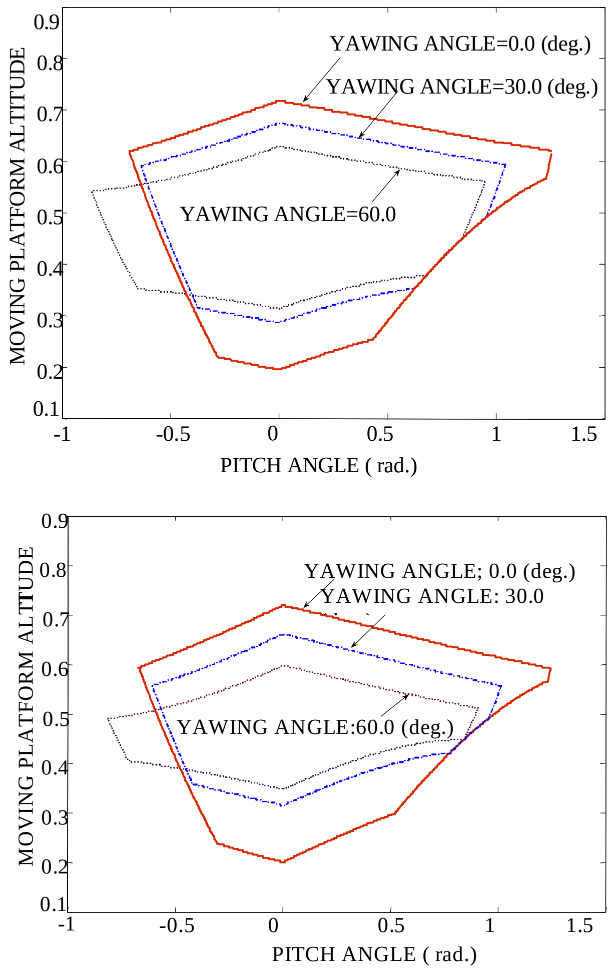


Figure 18. y=0, j=0.0, 30.0, 60.0 °, y=0, *x*=0 and y=0, the workspaces of pitch versus heave with the constraints of h_{Ps} > 0, h_{Qs} > 0 and angle q_p, (a) r = 0.15; (b) r =0.20.

with constant position (OWP) are analysed in this work[11-12].

If the vehicle size (radius of base platform *R*) and lengths (l_{max} and l_{min}) of the legs are given, the workspaces of surge, sway and pitch are only related with the radius of moving platform *r*. Assume the radius of base platform *R*=0.4, l_{max}=0.8 and l_{min}=0.4. For different radii of the moving platform *r*, the workspaces of surge, sway (PWO) and pitch (OWP) relative to heave are shown in Figs 16–18. The lines in Figs 16–18 represent workspaces limitation positions or the end-effector space boundaries. That is, the end-effector of moving platform can achieve every position inside the boundary. Figure 16(a) shows that the limitation positions of surge in different radius *r* are almost the same (about the range of ± 0.4). The figure also indicates that the smaller radius *r* has the lower altitude when the moving platform at the positive limitation positions of surge, but the results are contrary to the negative limitation positions of surge. Figure 16(b) shows that each positive and negative limitation positions of sway in different radius *r* are almost the same (about the range of ± 0.3). By comparing Fig. 17(a) with Fig. 17(b), the workspace of pitch versus heave have more restrictions for the constraint conditions of $h_{P_s} > 0$, $h_{Q_s} > 0$ and firing θ_p angle. Therefore, the 6-SPS mechanism utilised as a weapon manipulator for MUGV has smaller workspace than traditional 6-SPS manipulator.

Figure 17(b) shows that the smaller radius *r* with the larger workspace for pitch versus heave. By comparing Fig. 18(a) with Fig. 18(b), the workspace for pitch versus

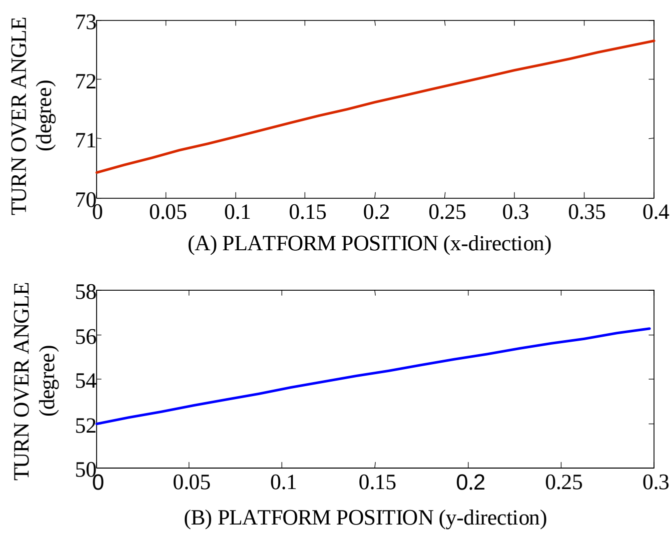


Figure 19. Gradability performance of 6-SPS mechanism: (a) forward ramp and (b) sideward ramp.

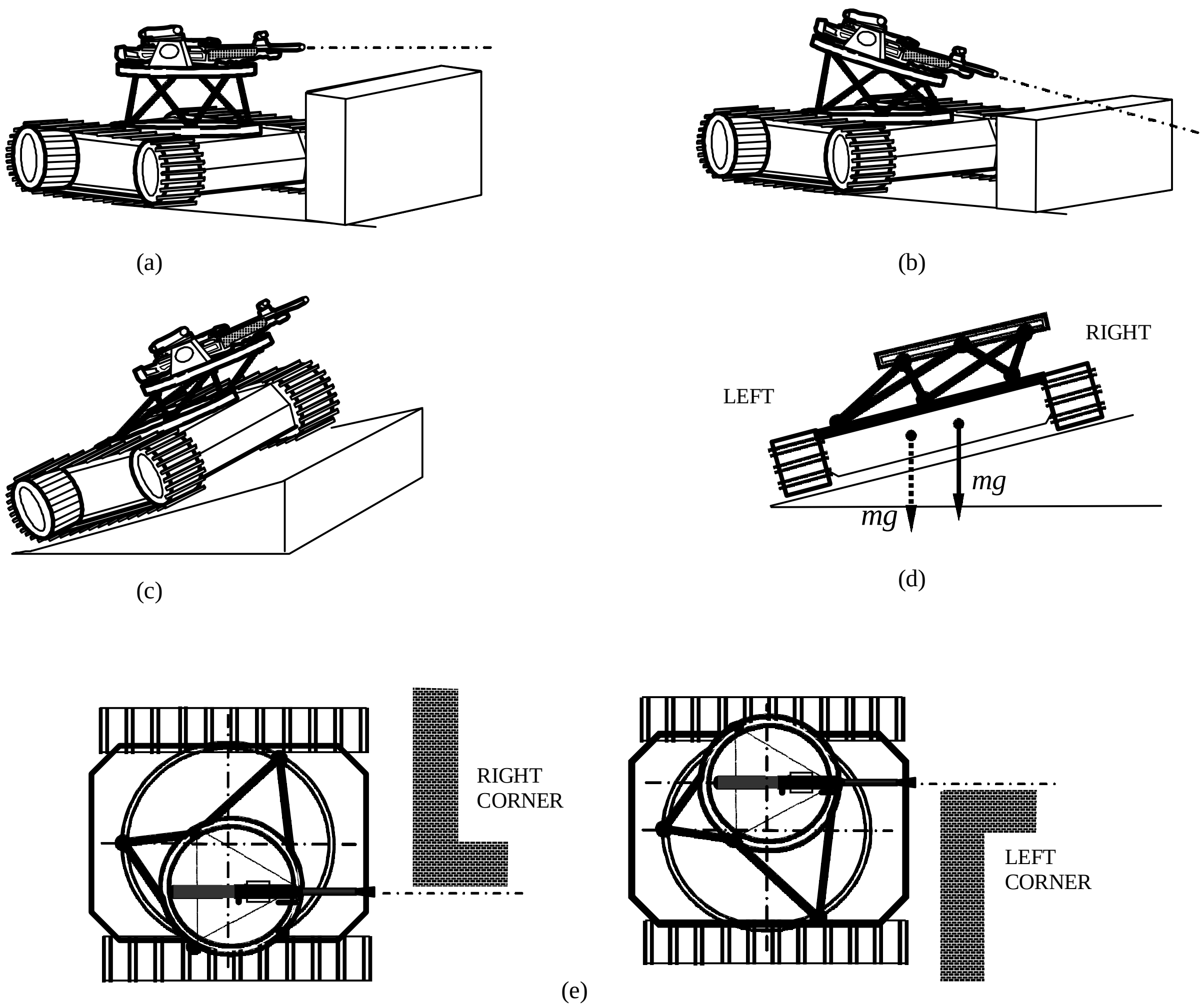


Figure 20. Abilities of 6-SPS mechanism: (a) surmount the high obstacle and fire; (b) shoot the target behind obstacle; (c) change the center of mass to forward; (d) change the centre of mass to right-sideward; and (e) take cover behind obstacle and fire at obstacle flank.

heave with radius r = 0.15 is greater than the workspace for pitch versus heave with radius r = 0.2 when the firing orientation angle θ_r (or yaw angle ψ) rotates to 30° or 60°. Furthermore, Fig. 18(a) and Fig. 18(b) indicate that pitch angle (firing angle) has larger variation range when moving platform (or machine gun) rotate to θ_r=60°. The reason is that shorter length of $\overline{OC}_{s1}$ leads to the larger inclination of machine gun when θ_r rotate to the direction of $\overline{OC}_{s1}$ (Fig. 15(c)). From above-mentioned, if the radius of base platform and the length of legs are given, the desire workspace can be designed by tuning the radius of moving platform.

3.3.2 Gradability Analysis

Assume the dimensionless mass of link 1 (vehicle body) is 1 and the dimensionless mass of moving platform is 0.35 (including the mass of machine gun and other payload). Figure 19 indicates that MUGV has better gradability performance on forward and sideward ramp when changing the moving platform positions.

From above discussion, the 6-SPS mechanism which is designed as a weapon manipulator has following characteristics: (a) the machine gun altitude can be adjusted, so that it can take cover behind different altitudes of obstacles and shoot the enemy (Figs 20(a) and 20(b)), (b) the center of mass of the whole system can be changed, so that it can achieve better operating stability when the system is operated on different gradients of ramps (Figure 20(c) and 20(d)), (c) the firing position can be shifted to right or left, so that it can take cover behind the obstacle and fire at the obstacle flank (Fig. 20(e)). These advantages are not present in other mechanisms. For these reasons, the mechanism can satisfy tactical needs completely. That is, the system is suitable for more complex gradual terrain.

4. PERFORMANCE SYNTHETIC ANALYSIS

To get a good applicable mechanism for a weapon manipulator, the performance synthetic analysis based on the view point of TREAs will be discussed in this section. The TREAs for different types of weapon manipulation mechanisms that work in different terrain features are shown in Table 1. The characteristics for each mechanism have been discussed in previous sections. Summarizing the comparisons, the 6-SPS and RRR have better performance

Table 1. Tactical requirements enforcing ability in different terrain features

Terrain features	Types of weapon manipulator mechanisms			
	1-RR	1-RPR	1-RRR	6-SPS
Ridge	×	×	•	•
Mound	Δ	•	•	•
Hole	×	•	•	•
Trench	×	⊕	⊕	•
Tree	⊕	⊕	⊕	•
Obstacle Flank	×	⊕	⊕	•

Ability Notation: •: Good; ⊕:Acceptable; Δ: a bit weak; ×: weak

in TREAs. However, the disadvantage of 6-SPS mechanism is that complex mechanism leads to complex control problem. The disadvantage of the RRR mechanism is that it has poor stiffness. Fortunately, these problems may be solved by advanced control methods. Furthermore, although the RR and RPR mechanisms have simple mechanism, the serious disadvantages of poor operation stability and TREAs cannot be solved in anyway.

5. CONCLUSIONS

In the future spectrum of war, the MUGV system will be critical equipment and become more and more important. In order to design a MUGV system that can competently enforce the tactical needs, it is important to design a weapon manipulator with higher performance. However, few studies have been done for this purpose. In this work, the design factors of the weapon manipulator on how to satisfy the tactical needs are considered, and two types of weapon manipulators designed as the serial robot, such as 1-RRR mechanism, and the parallel robot, such as 6-SPS mechanism, are proposed. The workspace analysis results demonstrate that the 1-RRR and 6-SPS mechanisms can be good design tactics. It can be used as the reference resource for the designer to design the weapon manipulator for the MUGV.

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