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Optimizing Hexapod Robot Reconfiguration using Hexa-Quad Transformation

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Article Info	ABSTRACT
	This paper presents a leg reconfigurable technique to optimize the hexapod robot reconfiguration flexiblity. A hexapod-to-quadruped (Hexa-Quad) transformation technique is proposed to optimize hexapod legs on certain situation that need some legs to be disabled as a leg to do other tasks and operations. This proposed method used the factor of center of body (CoB) stability in the support polygon and its body shape. The reinitialized leg's shoulder method is proposed to ensure the support polygon is balanced and confirmed the CoM nearly or at the center. This method is modeled and simulated in a real-time based model of hexapod robot with 4-DOF/leg control architecture. The model is verified in numerical model and presented using separated 3D simulators.

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1. INTRODUCTION

Multi-legged robot or so called active suspension vehicle (ASV) has significant advantages if compare to the wheel type robot especially on facing irregular and mountainous terrain. The advantages of multi-legged or legged robot can be seen obviously on inspired life living form; legged creatures. Raibert in his book has mentioned that only about half of the earth 's landmass is accessible to existing wheeled and tracked vehicles ,whereas a much larger fraction can be reached by animals on foot[1]. In multi-legged robot research and development, several studies have been done to achieve good adaptability, function, high flexibility and extensibility with extreme and unknown terrain. The progress emphasized in all expects and hierarchy of multi-legged system such as system mechanism, structure design/configuration, software development/control technique and electronics unit design. In control technique level, reconfiguration technique is one of the important parts in legged robot control, which is emphasized on recovery action [2] and multi-tasking. Therefore stability become a main point in this research that involving center of mass (CoM) of the legged robot and its support polygon. The larger the *support polygon* developed by the robots the bigger the probability for the robot to remain upright without overturning when it stops walking at any moment during the walking period, and this is called statically stable walking or static stability. Static stability occurs when CoM lies completely within the support polygon and the polygon's area is greater than zero, and hence static stability requires at least three points of ground contact [3]. Robot's CoM represented a significant aid in maintaining the stability[4] and as additional source of information in identified process and stability indicator. Moreover, CoM is calculated to provide critical to access rehabilitation success in pathology detection and in describing gaits[5]. In reconfiguration aspect, the CoM's of legged robot is will be reallocated since the changing of in the structure or leg configuration of the robot.

Therefore in this study, determination on hexapod configuration to quadruped configuration for a hexapod robot (Hexa-Quad) is proposed. Hexapod is one of the statically stable configurations of multi-legged robot that has potential to be reconfigured into less than six legs such as quadruped and bipedal configuration. Transforming hexapod to bipedal configuration is considered as critical configuration for hexapod unless there have a special design on leg configuration and robot body's shape itself (other than common hexapod's body shapes; square, trapezium, round or hexagon body). The quadruped configuration is selected since this configuration is in between statically and dynamically stable and suitable for any common shape of hexapod robot's body. Static stability assumes the vertical projection of the CoM always remain inside the support polygon with an adequate stability margin during all phase of movements [6]. On the other hand, dynamically stable depends on the stability during the robot is moving which demands on active actuation to maintain the balance and performing faster motion[7]. As part of dynamically stable configuration, quadruped legged robot configuration also practical on performing locomotion for complex terrain according to the several practical achievement reported in [8, 9].

Reconfiguration issue become one of the small sections in robotic issue that has potential to be explored in order to optimize the use of the default mechanism of the robot itself and increased its flexibility. CONRO from Polymorphic Robotics Laboratory of USC Information Science Institute is one of the examples of hexapod robot that performing proposed hormone-based distributed control to implement its gait reconfiguration between caterpillar and spider gait mode[2]. Shen *et. al.* mentioned that the number of supported leg must meet the stability criteria according to the number of leg that available for walking used. It is different to the hybrid wheel-legged robot, namely Hylos is designed and developed by Laboratoire de Robotique de Paris (LRP), Universit´e de Pierre et Marie Curie, France whereby to optimize both the balance of traction forces and the tipover stability. A specific trajectory and posture control is designed to overcome both robot's locomotion itself and orientation of the main body and sideway wheelbases [10].   On the other hand, OSCAR from University Lübeck has proposed the organic self-configurable in hexapod robot as its name implied. The aim of the development is to overcome the malfunction leg(s) and optimizing the overall energy during locomotion by performing self-amputation [11].

According to the study goal, both hexapod and quadruped robot stabled walking pattern is crucial. This is a fundamental problem need to be solved for every walking robot in moving operation. The development of walking pattern of a walking robot is a challenging task because the consideration the degree of freedom (DoF) with the support polygon is important for the stability of the robot [12]. Yang J.M. *et. al* in their studies has considered the analysis of the joint failure based on the manipulator kinematics and gait patern. Thus proposed the periodic quadruped and hexapod gait to overcome any fault tolerant caused by joint failure and to maintain the stability of the robot [13]. On the other hands, Tsujita K. *et. al* has overcome the timing problem between transverse, rotary, pace, bounce and trot gait pattern for quadruped robot studies considered the analysis on the suitable gait pattern for the quadruped robot by proposed the adaptive control [14]. Other effort has been done by proposed the Gait regulation technique to increase the robustness in multi-legged robot walking pattern. For a single duty of a developing gait pattern, need just ignore the kinematic mapping and the consideration of keep more legs contact with the surface. Due to the limitation recirculation speed, the trot and tripod gait pattern can perform signification faster than other[15]. According to the lift and release probabilistic events [3] for each leg of legged robot, tripod pattern for hexapod robot is less and producing faster movement. Quadruped robot on the other hand having between dynamic and static stability range which is required good combination of suitable walking pattern. Therefore, in this article, the combination of traverse and trot walking pattern has been proposed for the robot model in quadruped mode.

The proposed Hexa-Quad transformation for hexapod robot is designed with two different forms namely center legs disable (CLD) and side legs disable (SLD). The form is decided based on common application for the hexapod robot such as converting legs to the free manipulators or disabling the leg for energy saving. The proposed transformation technique is created by inspired from the CoM in support polygon and leg shoulder angle symmetrical concept proposed previous in [16]. The proposed transformation, tripod pattern and traverse-trot pattern are modeled in a hexapod robot real-time model with 4 DoF leg configurations.

2.   HEXA-QUAD TRANSFORMATION TECHNIQUES METHOD

Most of the proposed transformation techniques for multi-legged walking robot are due to the specific configuration of the robot itself. In this study, the transformation is proposed for general hexapod robot configuration with any number of DOF legs. The proposed Hexa-Quad transformation technique is designed by considering the support polygon or stability area of the robot as shown in **Figure 1** and **Figure 2**. The larger the support polygon developed by the robots the bigger the probability for the robot to remain upright without overturning when it stops walking at any moment during walking period, and this is called statically stable walking or static stability [3].
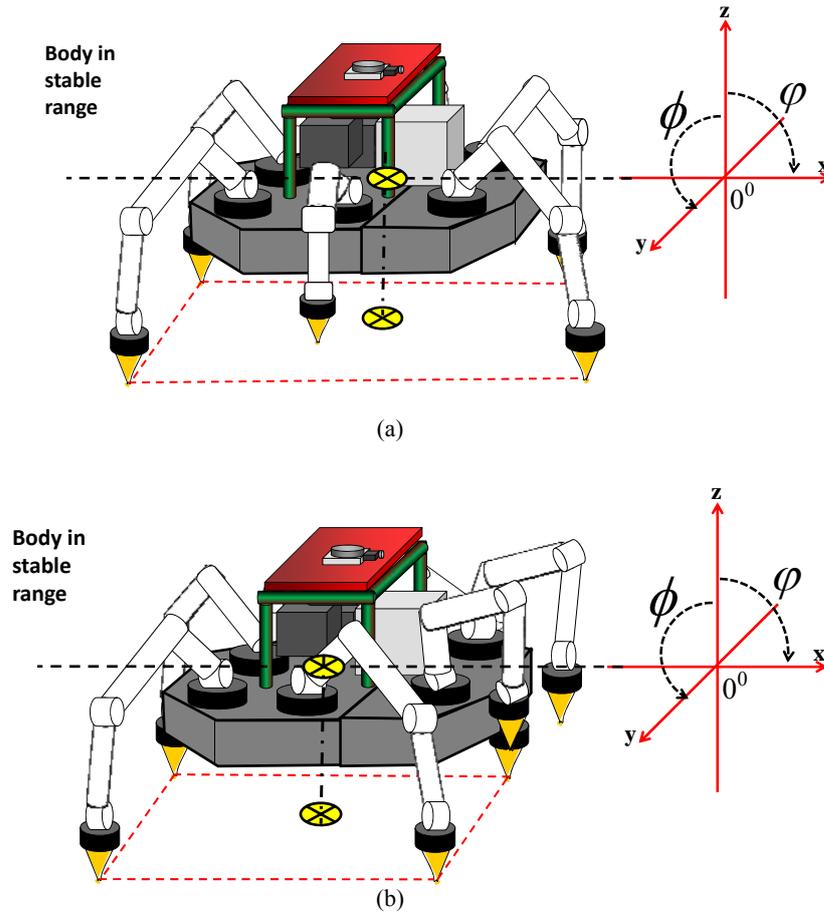
Figure 1. The proposed forms of Hexa-Quad transformation; (a) CLD form, (b) SLD form.

Therefore in proposed Hexa-Quad transformation technique, two forms of transformation are proposed by considering the support polygon and CoM as shown in Figure 1. CLD is realized by lifting up two center legs as in *sit down mode*. This form is not critical to control if compare to the SLD (Figure 1(b)) that required a proper initial standing position for other legs. Therefore, this proposed technique introduced separated calculation for CLD and SLD as shown in Figure 2 and Figure 3 respectively.

As shown in Figure 2, the CoM is at the center of the body (CoB) of the robot and the support polygon is followed by the shape of the standing legs. The shape of support polygon is depends on the number of touching leg on the ground (red dotted line) as shown in Figure 2 and Figure 3. Thus the new maximum extended angle of shoulder for each supporting legs (enabled legs) (θ_a) after transformation can be determined by using is the length (l) and width (w) of the robot body as follows;

$$\theta_a = 0.5\tan^{-1}\left(k\frac{l}{w}\right) - |\theta_{n_o}| = 0.5\tan^{-1}\left(k\frac{x_o}{y_o}\right) - |\theta_{n_o}|$$ (1)

where x_0 is the vertical length from the center of the robot body while y_0 is the horizontal length from the center of the body and θ_{n_o} is an initial value for each shoulder. In addition, k is tuning parameters in order to achieve $l_s \approx w_s$ to ensure CoM near the center of support polygon.
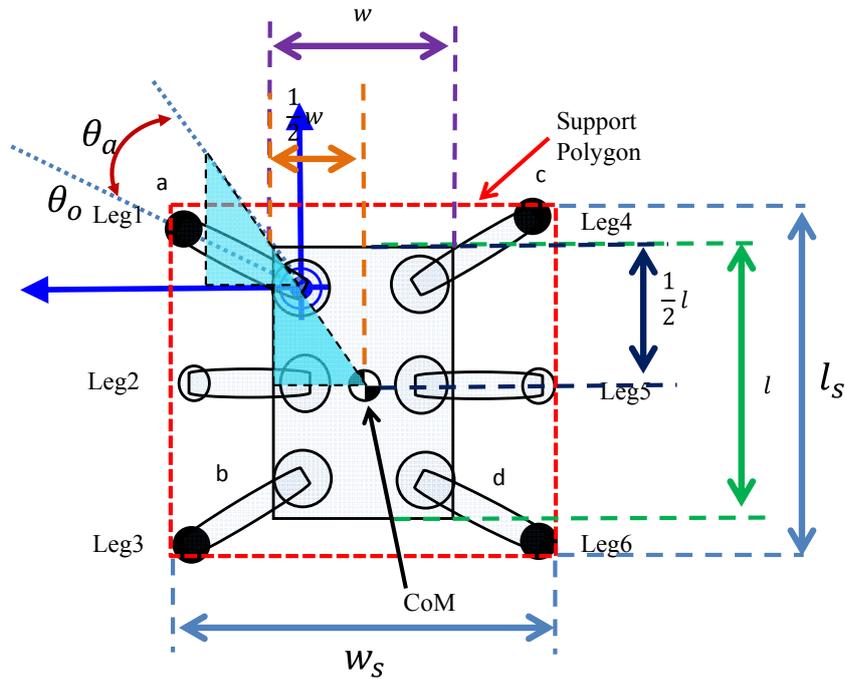
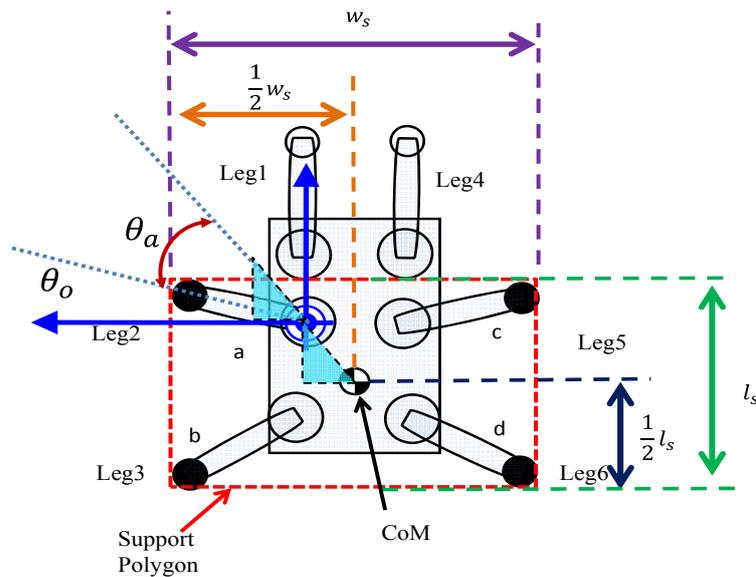Figure 2. Shoulder angle determination for CLD transformation mode.

Figure 3. Shoulder angle determination for SLD transformation mode.

This rule is applied with reference to the shoulder-based coordination system (SCS) and CoB-based symmetrical approach [16]. Moreover, the rule is very important for the proposed SLD form mode which is side legs are disabled from walking used. The other legs need to be reinitialized its shoulder's angle using Eq.1. As shown in Figure 3, example situation of two side legs (leg 1 and leg 4) is disabled and other four legs (leg 2,3,5 and 6) is reinitialized. The full transformation sequence of proposed Hexa-Quad is presented as finite state machine (FSM) as shown in Figure 4.

Robot body shape also the important factor that need to be considered on selecting proposed Hexa-Quad transformation form. Commonly, for default hexapod robot, the body design will considered the stable position for the leg to move and standing to ensure the CoM always at center of its support polygon. As shown in Figure 5, there are three different common shape of hexapod robot's body that possible to be

designed. Moreover the figure also shows that each shape has different support polygon size, l_s and w_s, with different body size, l and w. Figure 5(a) and 5(b) shows the $l > w$ and $w > l$ makes SLD method almost instable to be applied unless the support polygon size is tuned $l_s \approx w_s$ to better θ_a value such as Figure 3. It is same to the round body shape with the size $l = w$. Therefore it makes CLD method most likely suitable transformation form for common shape of hexapod robot such as existed established hexapod robots reported in [17, 18].
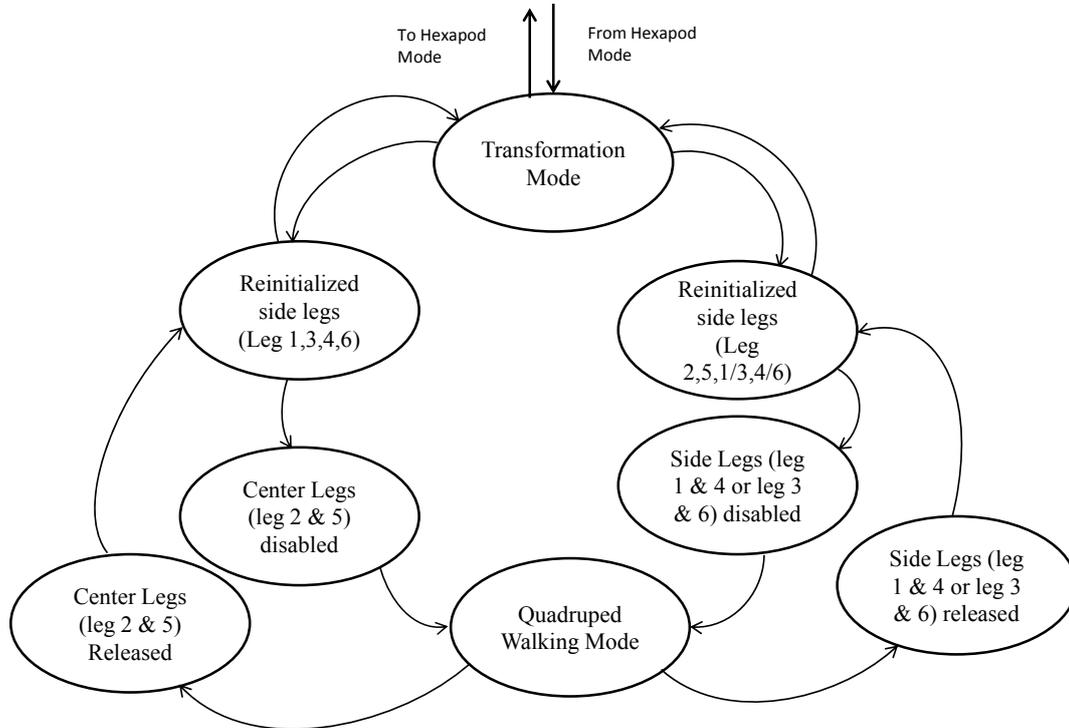
Figure 4. FSM of proposed Hexa-Quad transformation for hexapod robot model.
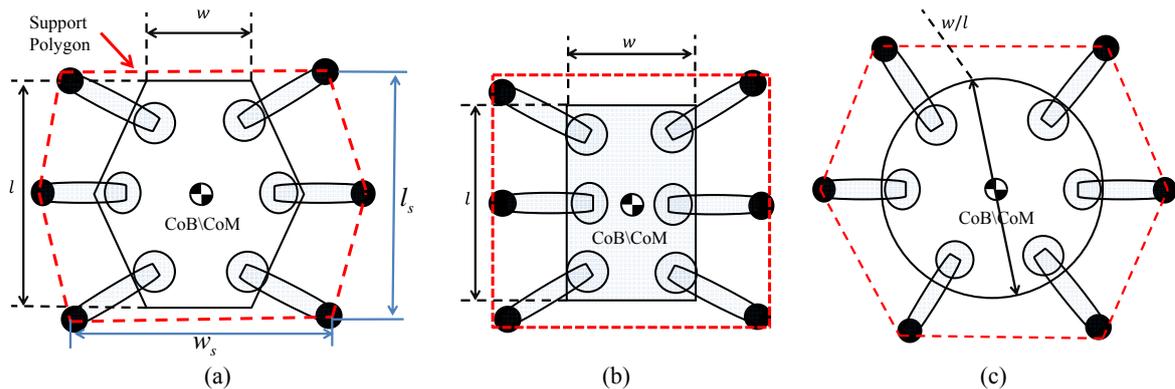

Figure 5. Fundamental shape for hexapod robot, (a)hexagon body shape, (b) Rectangular body shape, (c) Round body shape.

3. WALKING PATTERN AND SHOULDER-BASED COORDINATION SYSTEM

      The sequences of the legs for quadruped and hexapod walking are presented in finite state machine (FSM) as shown in Figure 6. On hexapod configuration or hexapod mode as shown in Figure 6(a), tripod walking gait pattern is used since it performs fastest walking with minimum area of support polygon in hexapod robot stability. On the other hand, traverse-trot gait pattern is selected for quadruped mode as shown

in Figure 6(b). This proposed quadruped mode gait pattern performing maximum two legs at a time during locomotion which is the fastest for this configuration. Furthermore transverse-trot gait patterns is used and designed with SCS kinematics reference as shown in Figure 7 since both hexapod and quadruped configuration modes are applied in the same hexapod robot model. In addition the force effective trajectory motion as shown in Figure 8 [19] is applied for both walking modes, thus the *support phase* and *swing phase* equations are generalized as expressed as Eq. 2 and Eq.3. Both positions including vertical leg position (z) is determined differently in each support and swing phase by using those equations respectively.
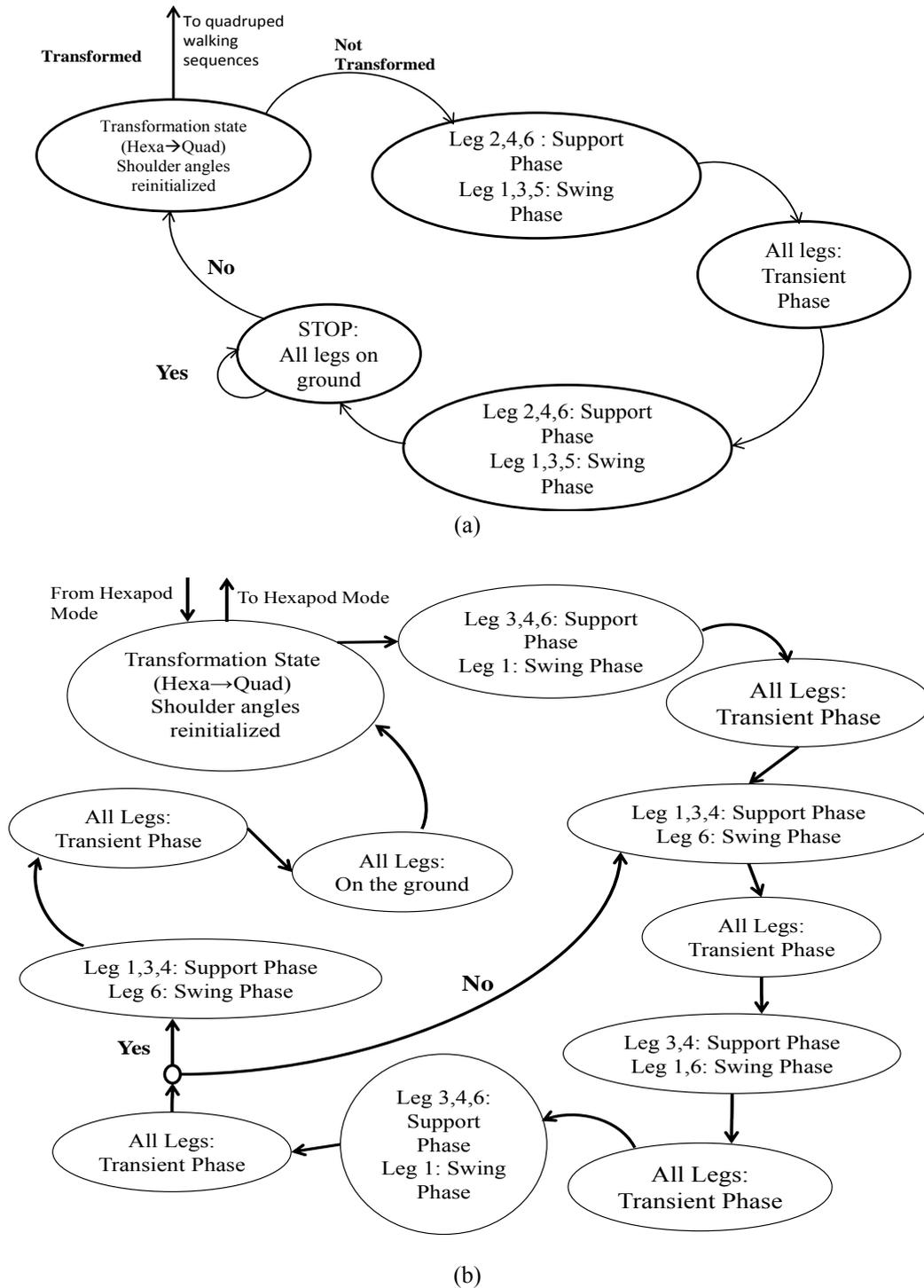

(a)

(b)

Figure 6. FSM for (a) tripod gait pattern and (b) traverse-trot gait pattern in hexapod robot model with Hexa-Quad transformation.

(Support Phase – Step and push on the ground) $0 \le t \le \dfrac{T_c}{2}$

$$x_{s_n}(t) = x_{0_n} + \frac{S_o}{4}\left(\frac{2t}{T_c} - \frac{1}{2\pi}\sin\left(\frac{4\pi t}{T_c}\right)\right)\cos\theta_{a_n}$$

$$y_{s_n}(t) = y_{0_n} + \frac{S_o}{4}\left(\frac{2t}{T_c} - \frac{1}{2\pi}\sin\left(\frac{4\pi t}{T_c}\right)\right)\sin\theta_{a_n}$$

$$z_{s_n}(t) = z_{0_n} \tag{2}$$

(Swing Phase) $0 \le t \le \dfrac{T_c}{2}$

$$x_{s_n}(t) = x_{0_n} + \frac{S_o}{2}\left(1 - \cos\left(\frac{2\pi}{T_c}t\right)\right)\cos\theta_{a_n}$$

$$y_{s_n}(t) = y_{0_n} + \frac{S_o}{2}\left(1 - \cos\left(\frac{2\pi}{T_c}t\right)\right)\sin\theta_{a_n} \tag{3}$$

$$z_{s_n}(t) = z_{0_n} + H_0\sin\left(\frac{2\pi}{T_c}t\right)$$

where,

      T_c = walking cycle time (s),

      t = update time (real-time) (s),

      t_{ex} = additional period for applying extra force (s),

      S_0 = distance of foot placement for one cycle (m), and

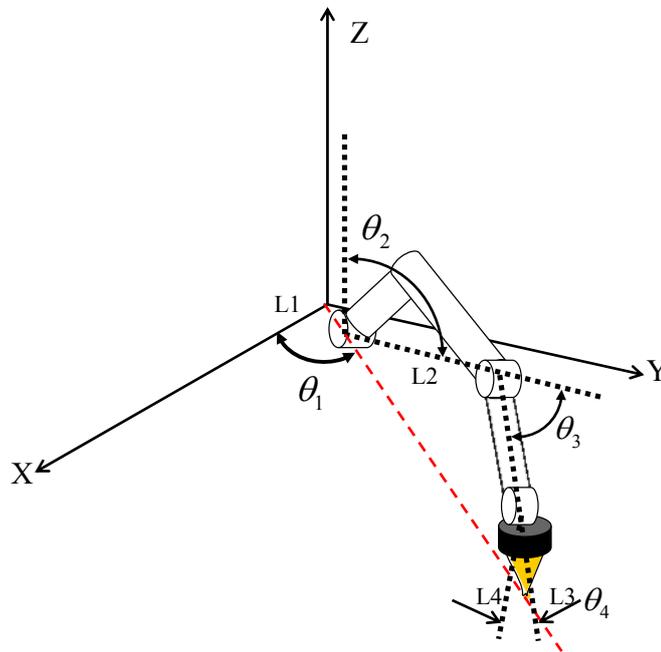 H_0 = height of leg lift from the initial position (m).

Figure 7. SCS trajectory kinematics motion for a 4-DOF leg of hexapod robot model with proposed Hexa-Quad transformation
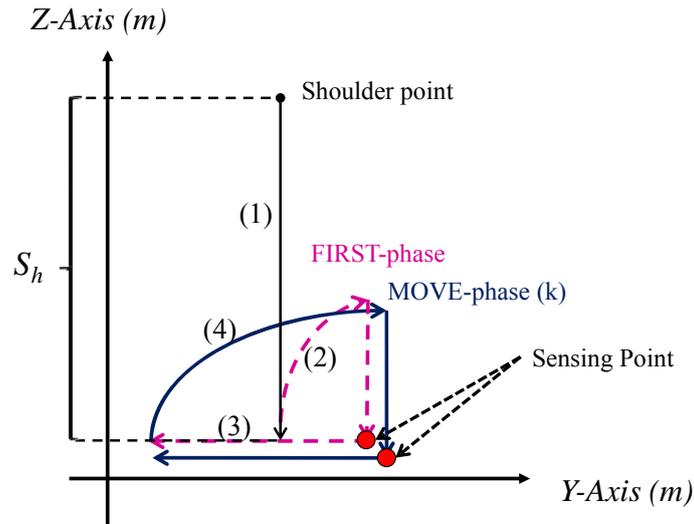
Figure 8. A leg motion shape used in hexapod robot model with proposed Hexa-Quad transformation

4. RESULTS AND ANALYSIS

Several simulations running have been setup and run to analyze the potential of the proposed method to be implemented in the real-time system. The first simulation in done on the proposed CLD method by simulating the real-time hexapod robot model with the 3D model that designed separately [20] as shown in Figure 9. Figure 9 shows the center legs (Leg 2 and 5) are disabled after robot stop walking in hexapod mode. In this case of transformation, side legs become main legs and ready for quadruped mode walking. The initial angle of each main leg for quadruped mode doesn't change much due to the calculation using Eq.1.

It is different to the SLD transformation whereby certain steps of initialization needs to be done on the remained legs that will be used in quadruped mode walking. As shown in Figure 10, center legs (Legs 2 and 5) and side legs are reinitialized (Figure 10(b) and (c)) to appropriate angle before another side legs (Leg 1 and 4) flipped to the front and disabled (Figure 10(d)).
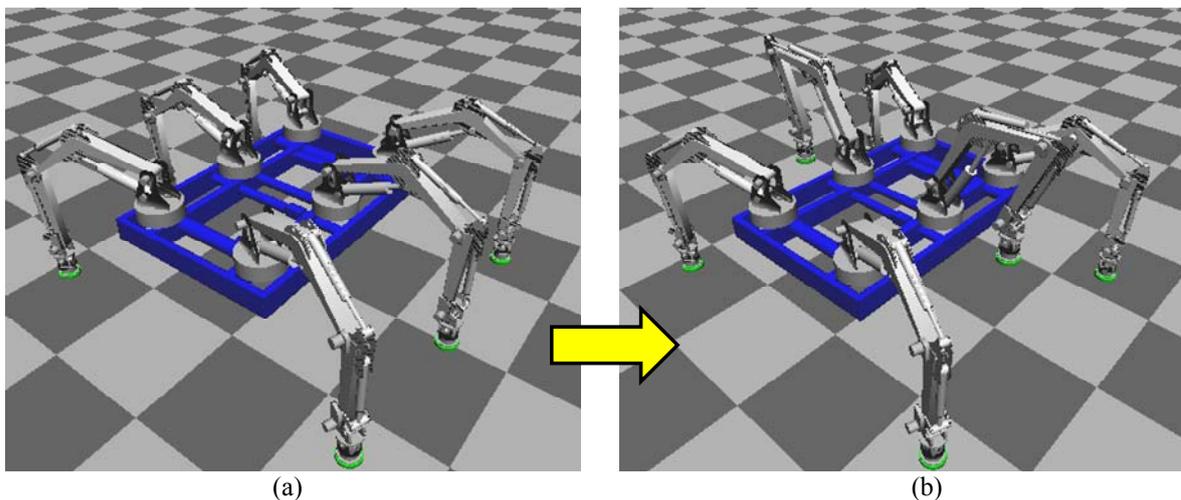

(a)   (b)

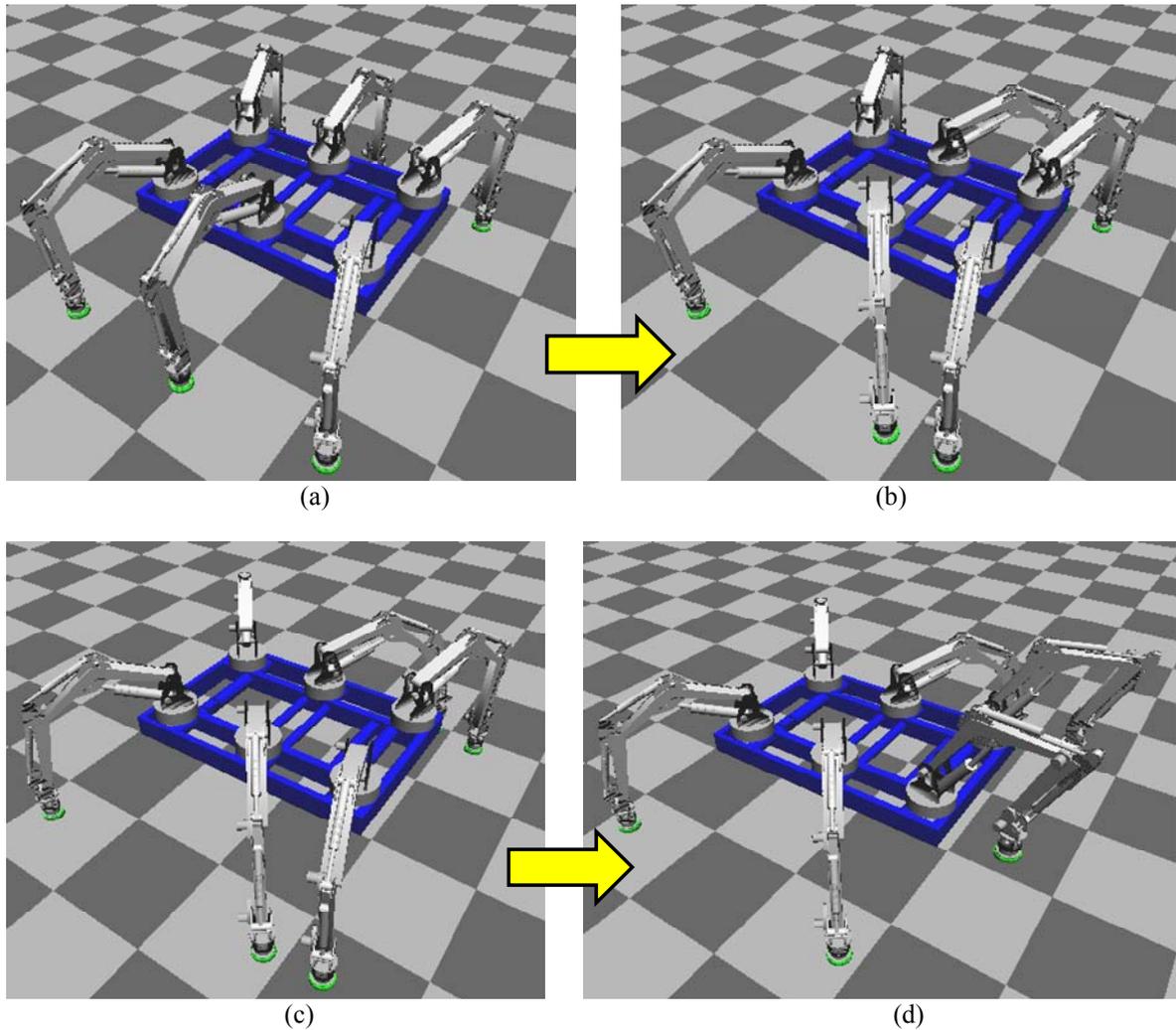Figure 9. 3D model simulation result for CLD transformation, (a) hexapod walking stop, (b) center legs disabled

Figure 10. 3D model[1] simulation result for SLD transformation, (a) hexapod walking stop, (b) center legs shoulder angle reinitialized, (c) side legs shoulder angle reinitialized, (d) target legs disabled.

This step is important to make sure robot is in stable range and overturning is avoided. Since the hexapod model with $l > w$, CLD is used to simulate hexapod mode to quadruped mode transformation. As shown in Figure 11, full walking from hexapod mode to quadruped mode is presented. The tripod walking is presented from Figure 11(a) to 11(b) and it stop for CLD transformation as shown in Figure 11(c). The robot continued walking in quadruped mode using proposed traverse-trot gait pattern from Figure 11(d) to Figure 11(f) in reverse path. As shown in Figure 11(c) center legs are disabled and all remaining leg done the traverse-trot walking gait pattern as shown detail in Figure 12 via foot motion sample results (z-axis). As shown in Figure 12(a), the foot motion started different *support phase* length after changing mode from hexapod mode to quadruped mode. Moreover for center represented by Leg 5 sample results in Figure 12(b) shows that foot motion is identically retain in initial position (sit down mode). On the other hand, body mass coordination (BMC) in Figure 13 shows stable line for both walking modes although in quadruped mode the path of walking is reversing hexapod robot.
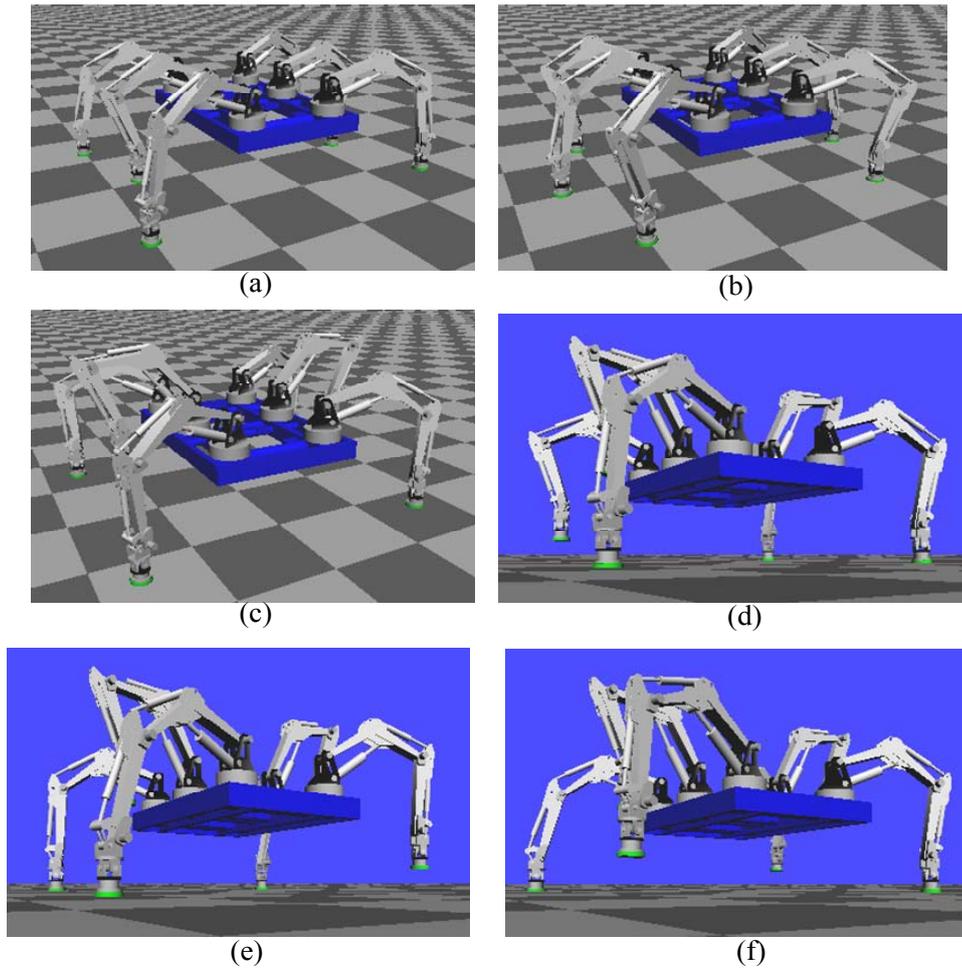

Figure 11. 3D model simulation results for full walking from hexapod mode to quadruped mode with proposed CLD Hexa-Quad transformation, (a) tripod cycle 1, (b) tripod cycle 2, (c) CLD transformation, (d) traverse cycle 1, (e) traverse cycle 2 and (f) trot cycle.
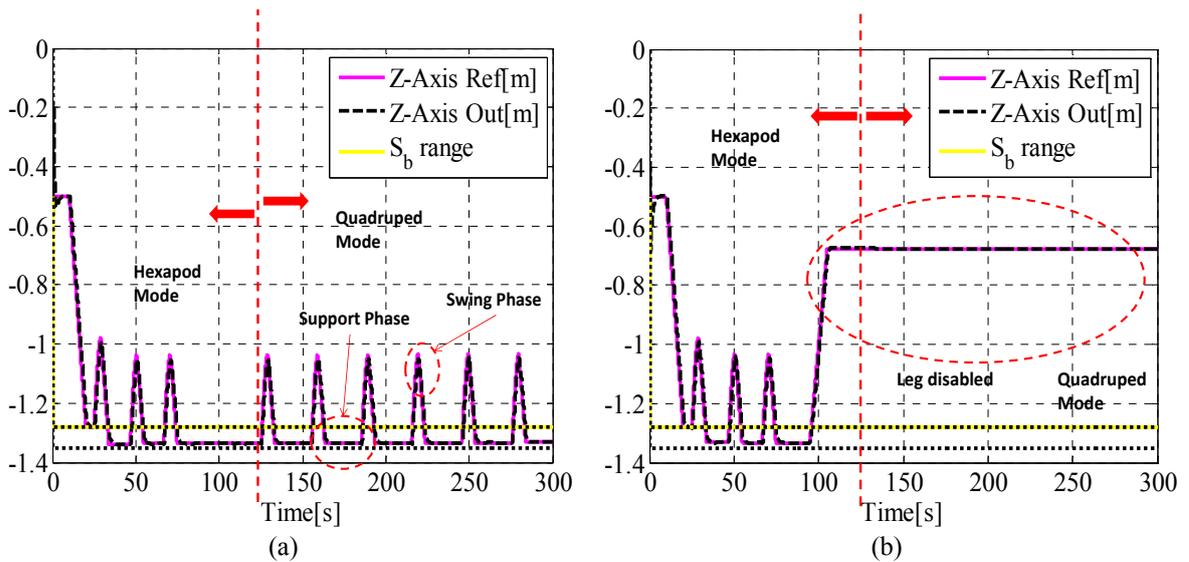

Figure 12. Position of the foot point on the z axis: (a) sample of leg 1, (b) sample of leg 5.
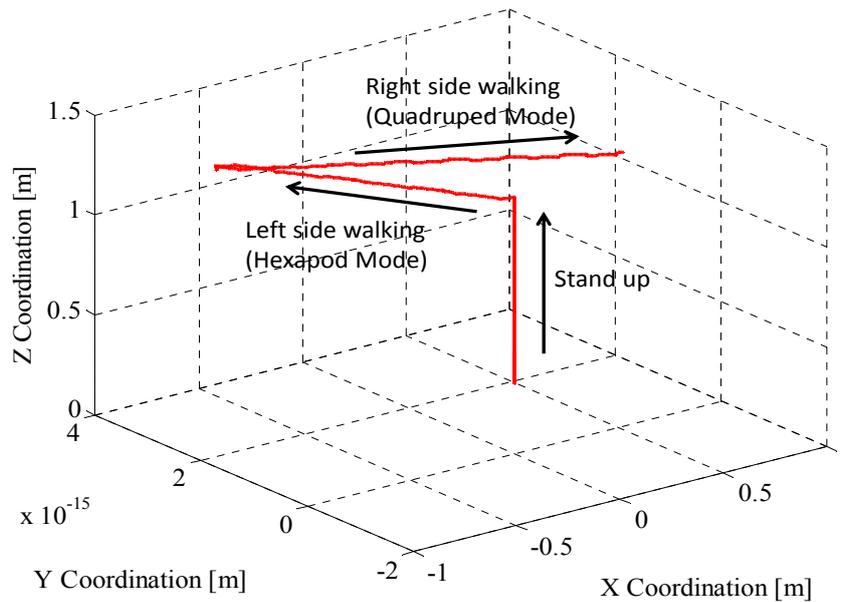
Figure 13. BMC results for hexapod mode to quadruped walking

5. CONCLUSION

The performance of both proposed Hex-Quad transformation methods have been presented. Through the series of simulations, it was shown that the proposed CLD method is suitable for common hexapod robot body with $l > w$ or $w > l$ dimension unless the body is flexible enough to balance the disabled legs postion after transformation if SLD is applied. Therefore on the next step progress, the research and development will be focused on enhancing the flexibility of the robot body to make sure hexapod body always at $l \approx w$ so that SLD is stable to be used.

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