Hexa-Quad Transformation Control for Hexapod Robot Based on Support Polygon Pattern

Addie Irawan[1], Yee Yin Tan[2], Mohd Syakirin Ramli[3], Mohd Riduwan Ghazali[4] and Kenzo Nonami[5]

[1,2,3,4]Robotics & Unmanned System (RUS) Group, Faculty of Electrical & Electronics Engineering, University Malaysia Pahang, Malaysia

[5]Division of Artificial Systems Science, Department of Mechanical Engineering, Chiba University, Chiba, Japan

[1]addieirawan@ump.edu.my, [2]yeeyin1228@gmail.com, [3]syakirin@ump.edu.my, [4]riduwan@ump.edu.my, [5]nonami@faculty.chiba-u.jp

Abstract: This paper presents a leg reconfigurable technique to optimize the multi-legged robot operation and walking performances. 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/operations. By separating two legs from the others, hexapod robot is able to be configured as quadruped robot configuration. Quadruped robot configuration is stand within dynamically and statically stable criteria if compare to the hexapod robot that has only statically stable criteria. Thus, it is very crucial to have a stable transformation technique during walking and operation session. Therefore Hexa-Quad is proposed with reference to the defined support polygon that based on its body area. A real-time based model of hexapod robot (4-DOF/leg) control architecture with Hexa-Quad transformation is designed and verified using separated 3D simulators.

Keywords: Hexa-Quad Transformation, center of mass, support polygon

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, control technique 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]. Quadruped legged robot configuration also practical on performing locomotion for complex terrain, due to the amount of researches that have been done on practical walking and motion control such as reported in [8-10].

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. In this article, the focus will be on the proposed Hexa-Quad transformation 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. The proposed transformation technique is created by inspired from the CoB and leg shoulder angle symmetrical concept proposed previous in [11]. The proposed transformation was modeled and applied on hexapod robot real-time model with 4 degree of freedom (DOF) and verified using separated 3D model developed previously in [12].

2 HEXA-QUAD TRANSFORMATION TECHNIQUE

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 **Fig. 1** and **Fig.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].

Therefore in proposed Hexa-Quad transformation technique, two forms of transformation are proposed by considering the support polygon and CoM as shown in **Fig.1**; center legs disable (CLD) and side legs disable (SLD). *Disable* here mean the legs are disable from walking command and separated from walking sequence.

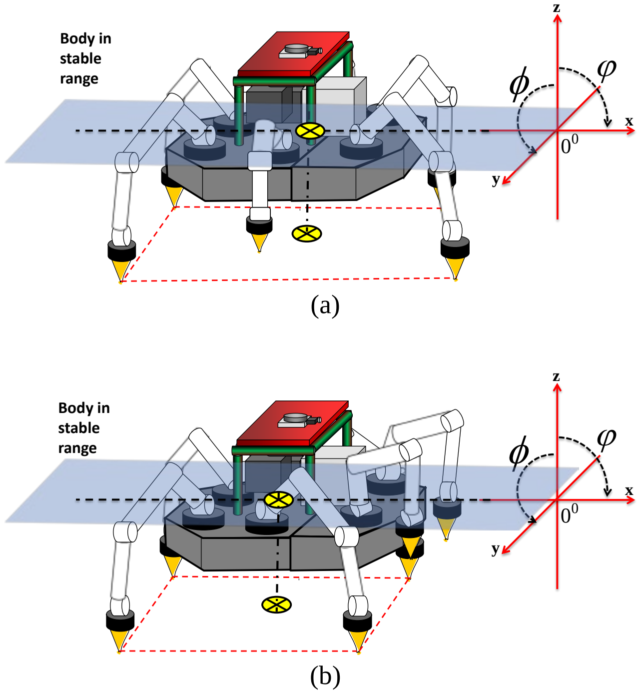


Fig 1. The proposed form of Hexa-Quad transformation; (a) CLD form, (b) SLD form.

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 (**Fig.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 **Fig.2** and **Fig.3** respectively.

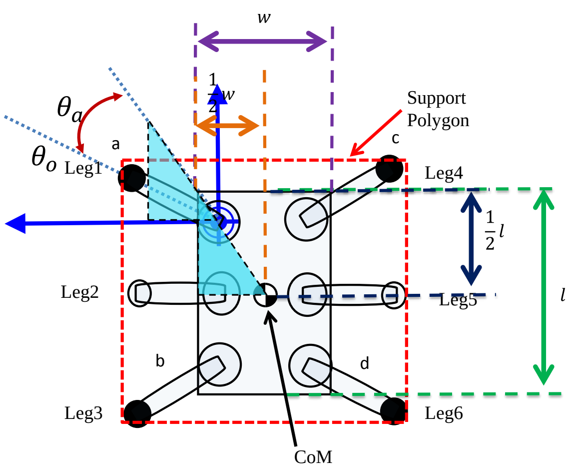


Fig. 2. Shoulder angle determination for CLD transformation mode.

As shown in **Fig.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 **Fig.2** and **Fig.3**. Thus the new 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;

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

where the area of robot's body $l \cong 2w$, 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. This rule is applied with reference to the shoulder-based coordination system [13] and CoB-based symmetrical approach[11]. Therefore, in this situation, the stability of the Hexa-Quad is achieved which CoM is within the support polygon and the area of the polygon is greater than zero. It is different to the SLD form mode whereby side legs are disabled from walking used and other legs initial angle for each shoulder is reset using **Eq.(1)**. As shown in **Fig.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 by using **Eq.1**. The full proposed Hexa-Quad transformation flow is illustrated via finite state machine (FSM) as shown in **Fig. 4.**

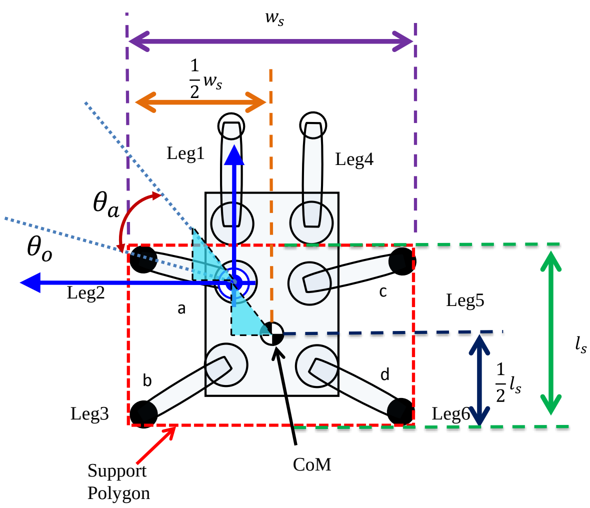


Fig. 3. Shoulder angle determination for SLD transformation mode.

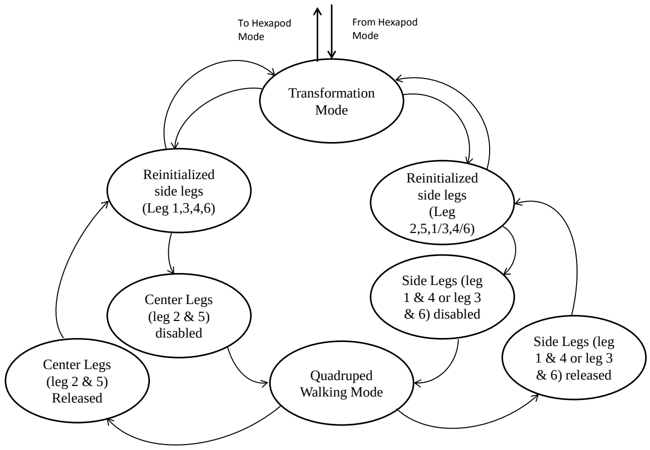
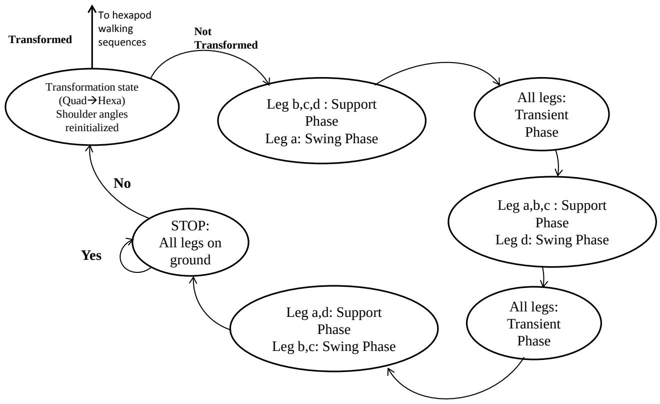


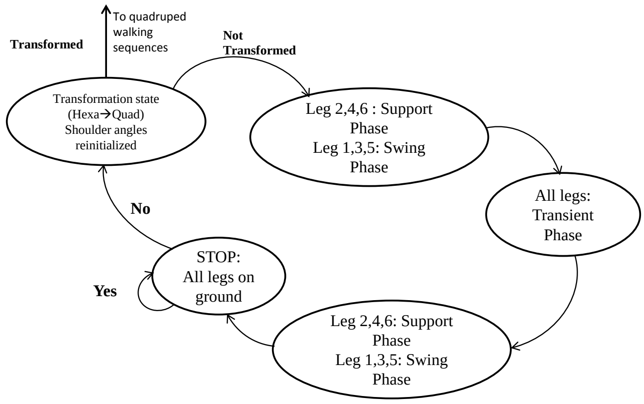
Fig. 4. FSM of proposed Hexa-Quad transformation for hexapod robot model.

3 WALKING PATTERN AND SHOULDER-BASED COORDINATION SYSTEM

Shoulder-based coordination system (SCS) was established implemented in the previous progresses for hexapod configuration such reported in [13,11] but not for quadruped configuration. For this transformation walking pattern, the combination of transverse and trot gait patterns [14] are used for the quadruped walking algorithm. The sequences of the legs for quadruped and hexapod walking are presented in finite state machine (FSM) as shown in **Fig 5 (a)**. On hexapod configuration or hexapod mode (see **Fig. 5(b)**), tripod walking gait pattern is used since it performs fastest walking with minimum area of support polygon in hexapod robot stability.



(a)



(b)

Fig. 5: FSM for (a) traverse and trot gait pattern and (b) tripod gait pattern in proposed model of hexapod robot with Hexa-Quad transformation.

As shown in **Fig. 5**, in transformation state, θ_a is changed and used on both x and y position of leg on the next sequences. x and y for each n-leg are part of moving frame and kinematics element for each link on each leg as shown in **Fig.6**. Both positions including vertical leg position (z) is determined differently in each support and swing phase by using **Eq.2** and **Eq.3** respectively.

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

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

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

$$x_{s_n}(t) = x_{0_n} + \frac{S_o}{2}\left(1 - \cos\left(\frac{2\pi}{T_c}t\right)\right)\cos\theta_{a_n}$$
$$y_{s_n}(t) = y_{0_n} + \frac{S_o}{2}\left(1 - \cos\left(\frac{2\pi}{T_c}t\right)\right)\sin\theta_{a_n} \quad (3)$$
$$z_{s_n}(t) = z_{0_n} + H_0 \sin\left(\frac{2\pi}{T_c}t\right)$$

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).

Both **Eq.2** and **Eq.3** were created to realize the motion shape as shown in **Fig. 6**. This motion shape is important for the force control implementation on each robot foot for walking on irregular terrain. As shown in **Fig.6**, (1) leg standing up, (2) swing phase (first step), (3) support phase, and (4) swing phase (next step).

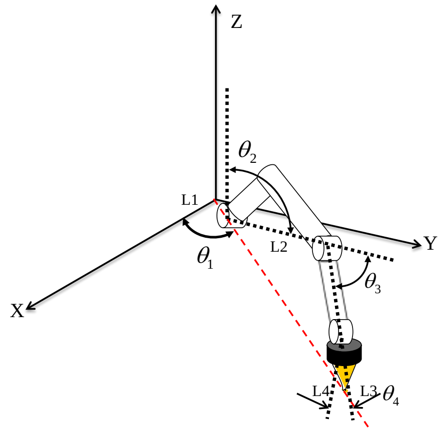


Fig. 6. SCS trajectory kinematics motion for a 4-DOF leg of hexapod robot model

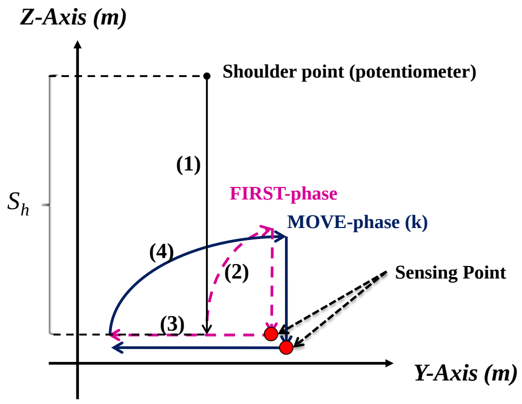
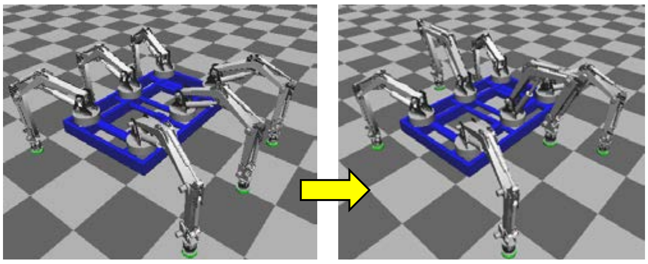


Fig. 7. A leg motion shape used in proposed model Hexa-Quad robot

4 SIMULATION AND RESULT

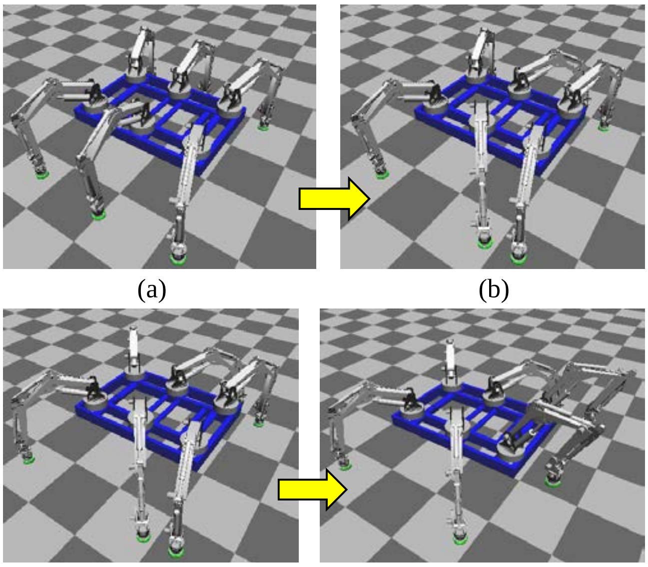
In this study, several simulations running have been done to analyze the potential of the proposed method to be implemented in the real system. The first simulation in done on CLD method by simulating the real-time system model with the 3D model that designed separately [12] as shown in **Fig.8**. On **Fig.8** it shows that center legs (Leg 2 and 5) are disabled after robot stop walking with hexapod mode. In this case of transformation, side legs become main legs that functional 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**.



(a) (b)

Fig. 8. 3D model simulation result for CLD transformation, (a) hexapod walking stop, (b) center legs disabled

It is different to the SLD transformation whereby certain steps of initialization need to be done on the main legs that will be used for quadruped mode walking. As shown in **Fig. 9**, center legs (Legs 2 and 5) and side legs are reinitialized (**Fig. 9(b)** and **(c)**) to appropriate angle before another side legs (Leg 1 and 4) are flipped to the front and disabled (**Fig. 9(d)**). This procedure of transformation to make sure robot are in stable range and overturning avoidance.



(a) (b) (c) (d)

Fig. 9. 3D model 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.

Quadruped mode walking is verified by simulating the performance of robot CoB [12] with comparison to the hexapod walking mode as shown in **Fig.10**. CoB representing body way point shows that both modes perform almost same results with the same omnidirectional angles inputs.

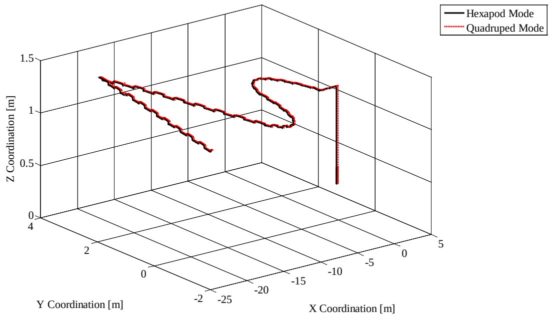


Fig.10 Omnidirectional walking simulation results for both hexapod and quadruped walking mode.

5 CONCLUSION

The performance of proposed Hex-Quad transformation technique has been presented. Through the series of simulations, it was shown that the proposed method performed stable reconfiguration on hexapod robot system to quadruped configuration with proposed reinitializing calculation. On the next step progress, the proposed method will be customized and applied on real-time hexapod system walking on actual environment.

6 ACKNOWLEDGEMENT

I would like to thanks to Research and Innovation Centre, University Malaysia Pahang on funding support on this research project. Also deep appreciation and thanks to my former supervisor, Prof. Kenzo Nonami from Chiba University, regarding his support on this research studies. Last but not least, also thanks to my students and associate researchers that involved in this research project.

REFERENCES

[1] Raibert MH (1986) Legged Robots That Balance. MIT Press,
[2] Wei-Min Shen, Salemi B, Will P (2002) Hormone-Inspired Adaptive Communication and Distributed Control for CONRO Self-Reconfigurable Robots. IEEE Transactions On Robotics and Automation 18 (5):700-712
[3] Siegwart R, Nourbakhsh IR (2004) Introduction to autonomous mobile robots. MIT Press, Massachusetts Institute of Technology Cambridge, Massachusetts
[4] Muscolo GG, Recchiuto CT, Laschi C, Dario P, Hashimoto K, Takanishi A A method for the calculation of the effective Center of Mass of humanoid robots In: 11th IEEE-RAS International Conference on Humanoid Robots (Humanoids), 2011 Bled, Slovenia, 2011. pp 371 - 376
[5] Cotton S, Murray AP, Fraisse P (2009) Estimation

of the Center of Mass: From Humanoid Robots to Human Beings IEEE/ASME Transactions on Mechatronics 14 (6):707-712

[6] Shugen M, Takashi T, Hideyuki W (2005) Omnidirectional Static Walking of a Quadruped Robot. IEEE Transactions On Robotics 21 (2)

[7] Freyr H (1997) Locomotion for difficult terrain. Royal Institute of Technology, Stockholm, Sweden,

[8] Raibert M, Blankespoor K, Nelson G, Playter R, TheBigDogTeam BigDog, the Rough Terrain Quadruped Robot. In: Proceeding of 17th World Congress, The International Federation of Automatic Control, Seoul, Korea, 2008.

[9] Hirose S (1984) A Study of desing and control of a quadrupped walking vehicle. International Journal of Robotics Research 3 (2):113-133

[10] Byl K (2008) Metastable Legged-Robot Locomotion. Massachusetts Institute of Technology, Massachusetts Institute of Technology Cambridge, Massachusetts

[11] Irawan A, Nonami K Force Threshold-Based Omni-directional Movement for Hexapod Robot Walking on Uneven Terrain. In: 2012 Forth International Conference on Computational Intelligence, Modelling and Simulation (CIMSiM), Kuantan, Pahang, Malaysia, 2012. vol 127-132. IEEE Computer Society,

[12] Ohroku H, Irawan A, Nonami K (2009) A 3D modeling for Hydraulic-drive Hexapod Walking Robot using 3D Geometric Technique with distributed Numerical Model. International Journal of Automation, Robotics and Autonomous Systems 9 (1)

[13] Irawan A, Nonami K (2011) Compliant Walking Control for Hydraulic Driven Hexapod Robot on Rough Terrain. Journal of Robotics and Mechatronics 23 (1):149-162

[14] Tsujita K, Tsuchiya K, Onat A (2001) Adaptive gait pattern control of a quadruped locomotion robot. Paper presented at the IEEE/RSJ International Conference on Intelligent Robots and Systems, 2001, Maui, USA,