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Fault tolerance criteria and walking capability analysis of a novel parallel–parallel hexapod walking robot

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SUMMARY

Fault tolerance is a very important issue for legged robots, especially in some harsh environments. One of the most fragile parts is the actuation system. There are two common faults of robot actuators: (1) the motor is locked and could not move anymore; (2) the motor is uncontrollable and can be treated as a passive joint. In this paper, we first discuss all fault combinations of a single leg of a hexapod walking robot with parallel–parallel mechanism topology. Then, the leg tolerable criterion is brought out, which defines whether a leg is fault tolerant. After that, the fault tolerance of the whole robot is researched, and we found that the robot can walk with one tolerable leg or two opposite tolerable legs. Finally, relative simulation results are given, which show the robot walk with one or two broken legs.

KEYWORDS: Hexapod robot; Fault tolerance; Locked failure; Uncontrollable failure.

1. Introduction

Robotic developments have greatly promoted human society. On the one hand, large-scale use in industry improves production efficiency and increases the social economic benefits. On the other hand, robots can protect human safety by working in arduous environments instead. Sometimes, it is very necessary to explore unknown and complex areas, which are dangerous for human beings,[1,2] such as nuclear plants, underwater environments,[3]de-mining tasks,[4] fired houses, and outer space planets.[5–8] Fortunately, we can turn to robots for help. All these areas have rough terrains, thus robots that have good terrain traversing properties are needed. Among all kinds of mobile robots, legged ones, such as hopping robots with one leg, biped human robots, quadruped robots, hexapod robots, and other legged robots with more legs, attract more and more researchers.[9] Legged robots show significant advantages compared with wheeled ones when walking over rough terrains because they do not need continuous contacts with ground. In nature, most arthropods have six legs to maintain static stability easily, and it can be observed that more legs do not increase their walking speeds. Hexapod robots also show better robustness in case of leg faults than biped or quadruped robots. For these reasons, hexapod robots have gained a lot of interests of international researchers during last several decades. Generally, hexapod robots can be grouped into two categories by their body shapes: rectangular and hexagonal. Rectangular hexapods have a rectangular body with two groups of legs, each consist of three, distributed symmetrically along the body. Hexagonal hexapods have a round or hexagonal body with evenly distributed legs. Wang and Ding[10,11] did lots of researches to compare the stability, fault tolerance, turning ability, and terrain adaptability of these two types of hexapod robots.

In some complex or harsh environments, robustness of hexapod robots is very important since maintenance of the robots is very hard or even impossible. Thus, fault tolerances of the robots are crucial for these applications and many scholars contributed a lot in this field. Kimura *et al.*[12]

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developed a fault tolerant control algorithm for space hyper-redundant manipulators.[12] For quadruped robots, Lee[13,14] derived a three-legged walking methodology with one broken leg. Pana[15,16] studied locomotion for quadruped robots with locked joints. Sousa and Krishnan[17,18] also did many researches on quadruped robot fault tolerances in recent years. Besides, Yang *et al.*[19–22] developed many kinds of fault tolerant gaits.

Yang also contributed a lot on hexapod robot fault-tolerance studies. He and his colleagues proposed schemes of fault detection and tolerant locomotion for even[23,24] and uneven terrains.[25,26] For one locked joint fault, Yang developed many different kinds of gaits, including tripod gaits,[27] crab gaits, turning gaits,[28] and omnidirectional walking methods.[29] Other issues such as gait synthesis[30] and kinematic constraints[31] have also been researched by Yang. Wang *et al.*[10] analyzed the typical locomotion of symmetric hexapod robot and improved some gaits both for normal and fault conditions. Robust swarm intelligence-based approach for the self-reconfiguration of a fault-tolerant hexapod walking robot was elaborated by Jakimovski *et al.*[32] Asif[33] improved navigability of hexapod robot using fault-tolerant adaptive gait. Chu and Pang[34] proved theoretically that hexagonal hexapod robots have superior stability margin, stride, and turning ability compared with rectangular robots when using fault-tolerant gait.

Although many works have been done up to now, the fault tolerant theory of legged robots still needs some complements. For example, in this paper, the hexapod robot is a hexagonal robot with parallel–parallel mechanism, thus the fault tolerant characteristics are different from those applying serial legs, for that both kinematic and dynamic models are different. Also, seldom works have been done on the impacts of faulted legs to the robots. In this paper, the leg tolerance of the robot is studied combined with the robot mechanism characteristics, such as work space. And whether the robot can walk with broken legs is discussed. The whole paper is organized as follows: Section 2 introduces a novel hexapod robot with parallel–parallel mechanism; then in Section 3, two basic kinds of actuator fault types are defined and all different fault types of single leg are synthesized; after that, in Section 4, a fault tolerant criterion of single broken leg is proposed and all leg fault combination types are analyzed using this criterion; in Section 5, impacts of broken legs to the robot are studied; finally in Section 6, relative simulation results are given, which show that with proper inputs the robot is tolerant with actuator faults.

2. Prototype

Hexapod robot in this paper is a parallel–parallel walking robot designed for nuclear disaster relief tasks. Up to now, two generations have been developed. Figure 1 shows the latest generation prototype. The whole robot consists of four parts: mechanical system, control system, sensor system, and energy supply system. In the mechanical system, the robot has a hexagonal body and evenly distributed legs, thus it is isotropic on all leg directions. The parallel leg mechanism includes an up-platform (the body) and a down platform (the calf). They are connected via three chains: one UP (universal and prismatic joints) chain and two UPS (universal, prismatic, and spherical joints) chains. At the end of the calf, a spherical hinge is installed to connect the foot. All prismatic joints are active and driven by electric motors via ball screws. The position of the calf with respect to main body can be controlled precisely by these motors. The passive spherical hinge at the end of the calf provides three passive DOFs (degree of freedom) that make the robot adaptable to uneven ground. On the passive joint, a damping spring is installed to reduce the impact force to the foot.[35] Hence, with respect to the main body, the calf has three active DOFs, but the foot has six DOFs among which three are active and the others are passive. During plan process, since the spherical joint is passive, the attitude of the foot is not controllable. Thus, the end-effector (EE) position is defined to be the three-dimensional Cartesian position of the calf as in Fig. 2. In our kinematical model, the EE position (x, y, z) is relevant with the input (l_1, l_2, l_3).

In the mechanism system, all three chains are equally responsible for achieving commanded calf positions, but in fault tolerant analysis, they can be divided to two groups: the main chain and the assistant chains. The UP chain is different from the other two chains, thus the fault on this chain is distinctive and it is regarded as main chain. The two UPS chains are exactly the same with each other except that their locations are symmetric, hence effects of faults on these chains are similar to each other and they are regarded to be assistant chains.

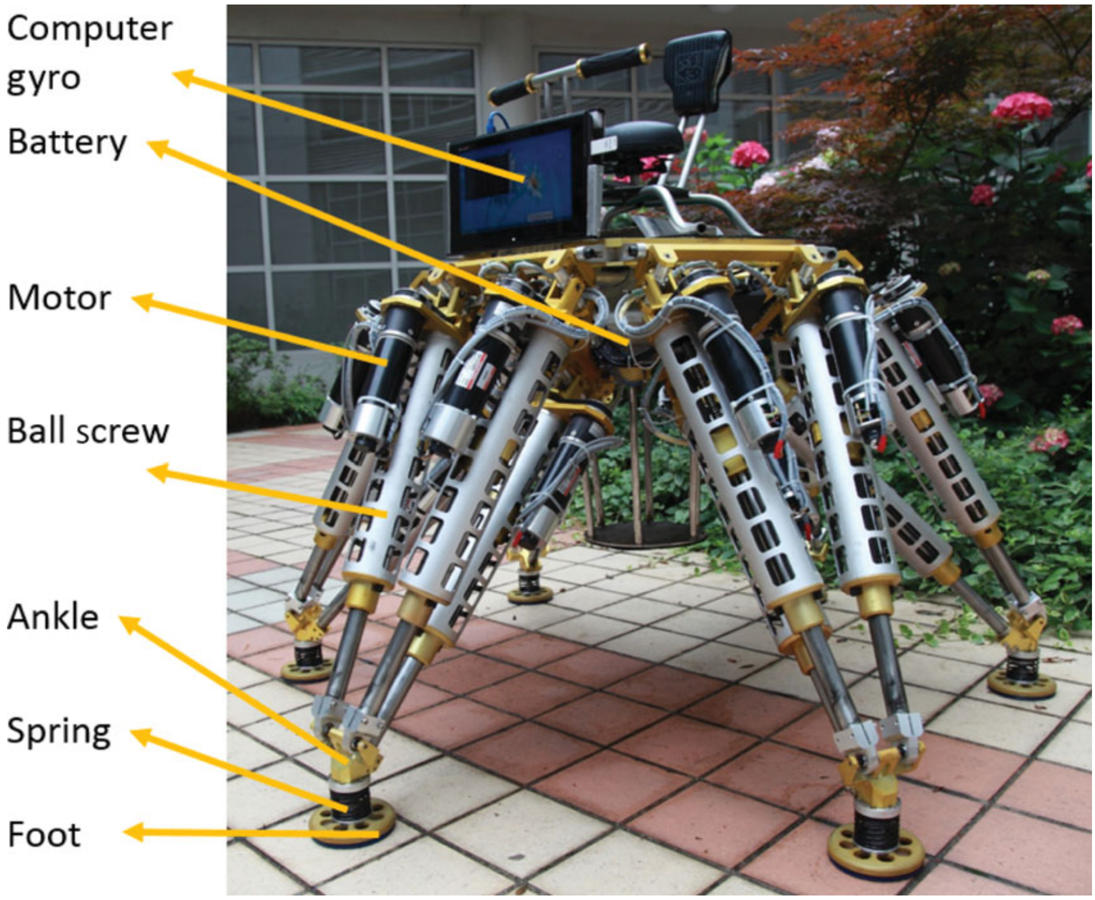


Fig. 1. Six-legged robot’s major components.

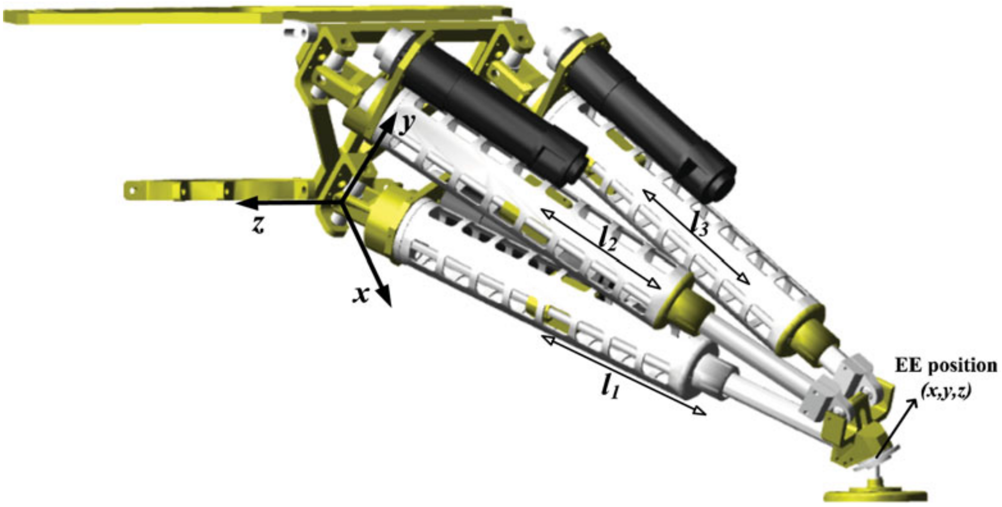


Fig. 2. Sketch of a single leg.

The robot control system includes: one computer, one master controller, and 18 actuators. The computer receives orders from the user and based on these orders, it generates corresponding robot body and leg paths. The master controller is in charge of generating trajectories for each motor based on the path plan. Then, every actuator can drive the associated electric motor.

Currently, the robot sensor system only has a gyro, which is used for measuring attitude of the robot body. The attitude data are transferred into the computer in real-time to assist the control system to generate the path plan.

The power is supplied by four lithium batteries with which robot can walk continuously for more than 5 h. Besides, more batteries can be installed on the robot back to expand its working time if endurance capacity is concerned.

In nuclear disaster relief processes, robots must fulfill tasks like exploring environment, transporting heavy stuffs, and manipulating devices. Radiation, obstacles, high temperature, and high pressure might lead faults to robot actuation systems. If one or more legs are broken, the robot needs to continue walking or operating with the broken legs, because repairs of the faulted legs are almost impossible after the robot has been sent to the disaster environment. So it is very necessary to analyze robot actuation fault tolerance. Common faults of actuators can be grouped into two categories: locked and uncontrollable faults. When the motor driver or other electronic components were damaged but mechanical parts were still in good conditions, these actuators still can stay at known positions with their breaks locked. Because of the locked breaks, the faulted actuators still have load-bearing capabilities, which eventually lead to the relevant chains are locked at known positions too. These kinds of faults are called "locked faults" in this paper. The other fault type is uncontrollable, which means the motor could not be driven nor locked. These faults could happen when robot mechanical parts are broken, e.g., the motor break is broken, or the belt pulley is fractured. The relevant chains are now uncontrollable and may swing randomly, thus the active joints actually become passive ones and they cannot afford loads any more. This paper studies the impacts of these two kinds of faults to the hexapod robot using parallel–parallel mechanism.

3. Fault Combination of a Single Leg

There are three actuators in a leg and two kinds of actuation faults, so there are many combinations of actuation faults for a single leg. Thus, all these combinations should be enumerated. The fault combination can be expressed like $A_L B_N C_U$, where A, B, and C stand for the 1, 2, and 3 chains of the leg mechanism; L, N, and U stand for the actuator states: locked, normal, and uncontrollable, respectively. Then, $A_L B_N C_U$ means that in the leg chain 1 is locked, chain 2 is normal, and chain 3 is uncontrollable. However, as we have mentioned in Section 2, the effects of faults on two assistant chains are similar to each other, e.g., the left work-spaces when chain 2 or 3 is locked are similar, so faults on chains 2 and 3 should be treated as the same type. Then, chains 2 and 3 can use one single character to denote both of them, e.g., $A_N B_L C_N$ and $A_N B_N C_L$ are all expressed as $A_N B_L B_N$, because both of them are the situations that only one assistant chain is faulted. The basic tool to analyze the fault combinations is the knowledge of combinatorics. In this paper, we let $C(n, r)$ denote the formulae of combinations to avoid repetition, which means choosing r elements from n. The detail is shown as follow:

$$C\left(n, r\right) = \frac{n!}{r!\left(n-r\right)!} \tag{1}$$

Combining with Table I, when only one actuator is faulted, it may occur at two possible positions: the main chain or the assistant chain. The fault also has two possibilities: L and U. Let S_1 denote possibilities of a single leg with one fault, hence the following result can be obtained:

$$S_1 = C\left(1, 2\right) \cdot C\left(1, 2\right) = 4 \tag{2}$$

When the leg has two faults, the possible positions of these two faults could be: both of them are on the assistant chains or one of them is on the main chain, while the other one on the assistant chain. The former situation also has three subtypes: both assistant chains are locked, both of them are uncontrollable, or one is locked and the other is uncontrollable. For the later situation, the main chain could be locked or uncontrollable, so as the assistant chain. Thus, the fault combinations can be calculated as follow:

$$S_2 = C\left(1, 3\right) + C\left(1, 2\right) \cdot C\left(1, 2\right) = 7 \tag{3}$$

Table I. Fault combination of a single leg.

	Chain property and fault type				
No. of fault	A	B	B	Symbol	Total
1	L	N	N	$A_L B_N B_N$	4
	U	N	N	$A_U B_N B_N$	
	N	L	N	$A_N B_L B_N$	
	N	U	N	$A_N B_U B_N$	
2	N	L	L	$A_N B_L B_L$	7
	N	U	U	$A_N B_U B_U$	
	N	L	U	$A_N B_L B_U$	
	L	L	N	$A_L B_L B_N$	
	L	U	N	$A_L B_U B_N$	
	U	L	N	$A_U B_L B_N$	
	U	U	N	$A_U B_U B_N$	
3	L	L	L	$A_L B_L B_L$	6
	L	U	U	$A_L B_U B_U$	
	L	L	U	$A_L B_L B_U$	
	U	L	L	$A_U B_L B_L$	
	U	U	U	$A_U B_U B_U$	
	U	L	U	$A_U B_L B_U$	
Total					17

When there are three faults in the leg, we can treat two assistant chains together as a part, just as stated before, which has three types. After that, the main chain also has two possibilities: locked or uncontrollable. So, the total number is listed as follow:

$$S_3 = C\,(1, 3) \cdot C\,(1, 2) = 6 \tag{4}$$

Table I illustrates all possible fault combinations of a single leg. As we can see, the total number is 17, including 4 kinds of one fault, 7 kinds of two faults, and 6 kinds of three faults.

4. Analysis of Broken Leg

4.1. Fault tolerance criteria

All fault combinations of a single leg have been analyzed in the last section; however, not all of them can be tolerated for two reasons: (1) the leg may lie down to the ground, and (2) the leg may clash with its neighboring legs. The second situation can be handled by adjusting the motion plan, e.g., the robot good legs can try to plan their trajectories to avoid clashing the faulted leg. Figure 3 shows overlapping work space of neighboring legs, and it is obvious that it is possible to plan the good leg trajectories beyond the faulted leg work space. Then, only reason 1 should be considered.

If chains are uncontrollable, the leg could fall down to the ground as a result of gravity. Then, if the robot still tries to walk, the broken leg will lie on the ground hitting and rubbing, and eventually causes the robot stumbled or even fall. This process can be seen in the left picture of Fig. 4 and this kind of broken leg is defined to be fault-intolerable. In other cases, such as main chain actuator is locked, but assistant chain actuators are normal, then we can control the broken leg to lift up to a position where the foot neither interfere with the ground nor with other legs. Thus, this broken leg does not affect robot walking, and this kind of broken leg is defined as fault-tolerable. The process can be found in the right picture of Fig. 4.

The robot is designed to work in different complex environments with heavy loads on its back. To keep the load steady while moving, the center of gravity (COG) should maintain at the same height and the robot body should not lean or roll either. Therefore, the robot height H (Fig. 4, left) is a constant value while walking. To avoid interference with ground, the broken-leg height h (Fig. 4,

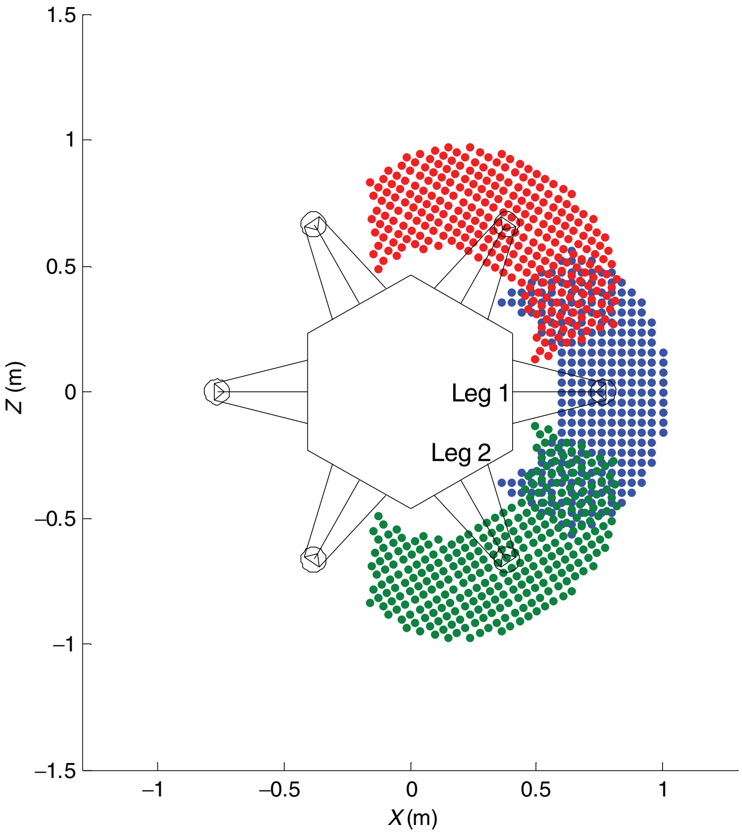


Fig. 3. Overlapping leg work spaces.

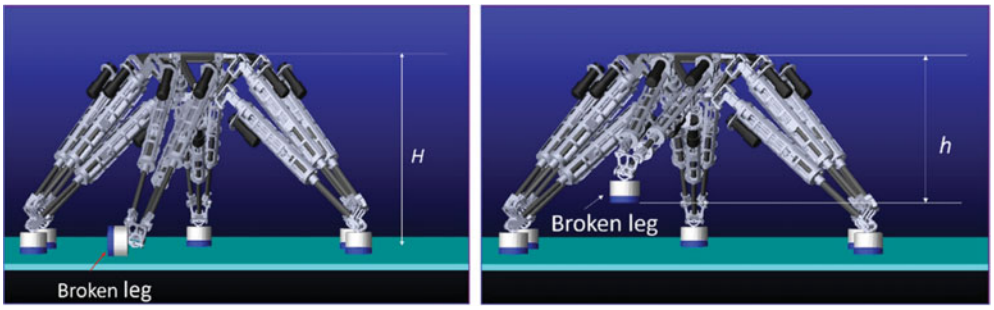


Fig. 4. Two types of broken leg.

right) should be higher than the ground. Thus, the condition of leg tolerance is that: there exist a set of inputs, which makes h smaller than H during the walk process.

When a broken leg only contains locked faults, the work space of the EE (the calf) of leg becomes a subspace of the normal leg work space. If this subspace has a subset above the supporting plane, the broken leg is considered to be fault-tolerable. When a broken leg only has uncontrollable faults, the EE of the leg is out of control because the uncontrollable actuation is at a random position. In this case, we need to find out an element of input set, which makes the EE trajectory always above the supporting plane.

In this paper, as Fig. 2 shows, l_1 denotes length of the main chain, l_2 and l_3 denote lengths of the assistant chains. Meanwhile, $l_{\min}$ and $l_{\max}$ are the minimum and maximum length of one chain. That is,

$$l_{\min} \leq l_i \leq l_{\max}, \quad i = 1, 2, 3 \tag{5}$$

Table II. Types of robot with failure.

No. of faults	No. of faulted legs	Formula	Total
1	1	$C(1,4)$	4
	2	0	
2	1	$C(1,7)$	37
	2	$C(1,3)\cdot(C(1,4)+C(2,4))$	
3	1	$C(1,6)$	90
	2	$C(1,3)\cdot C(1,4)\cdot C(1,7)$	
4	1	0	156
	2	$C(1,3)\cdot[(C(2,7)+C(1,7))+C(1,7)\cdot C(1,4)]$	
5	1	0	126
	2	$C(1,3)\cdot C(1,7)\cdot C(1,6)$	
6	1	0	63
	2	$C(1,3)\cdot(C(2,6)+C(1,6))$	
Total			476

However, one should note that not all inputs in this range are allowable, because some inputs may not obey basic geometrical principles. For example, the input $\{l_1 = l_{\min}, l_2, l_3 = l_{\max}\}$ is not allowable because the mechanism cannot achieve to this configuration physically and the forward kinematic model does not have real solutions.[35] Thus, when uncontrollable faults happened, the actual swing range of the faulted actuation is smaller than $(l_{\min}, l_{\max})$.

4.2. Broken leg with one fault

When a broken leg only contains one actuator fault, there are four combinations according to Table II. These combinations should be discussed separately, and here $A_L B_N B_N$ is analyzed first. Suppose l_1 is locked at length s, then the reachable work space L_S of the leg can be expressed as:

$$L_S = \{(x, y, z) | l_1 = s, \quad l_{\min} \le l_2, \quad l_3 \le l_{\max}\} \tag{6}$$

where (x, y, z) is the EE position with respect to body coordinate frame. So whether the broken leg can tolerate the fault depends on whether there exist a pair of $\{l_2, l_3\}$, which makes the EE position (x, y, z) above the supporting plane.

Figure 5 shows the subspaces L_S with l_1 locked at different places. Because the calf only has two DOFs under this condition, the work subspace L_S becomes a curved surface. For the robot, supporting plane is $Y = -550$ (mm) plane. It is obvious that no matter where l_1 was locked, there always exists a set of l_2 and l_3 that make the broken leg stay above the supporting plane. Thus, we can conclude that when a broken leg only has one locked fault in its main chain, wherever the locked position, this broken leg is fault-tolerable.

The similar analyzing method can be applied on the fault-type $A_N B_L B_N$. Figure 6 shows the subspaces L_S with l_2 locked at different places. It can be noted that each subspace has a subset above the supporting plane $Y = -550$ (mm). So the same conclusion can be made: when a broken leg only has one locked fault in assistant chain, wherever it was locked, the broken leg does not influence the robot walking.

For uncontrollable fault-type $A_U B_N B_N$, the calf of the broken leg can swing along a spatial curve with some fixed inputs. This trajectory T_U can be defined as follow:

$$T_U = \{(x, y, z) | l_2 = a, \quad l_3 = b, \quad l_{\min} \le a, \quad b \le l_{\max}\} \tag{7}$$

where (a, b) is an element of input set of l_2 and l_3. Figure 7 illustrates the EE trajectories with different l_2 and l_3. From the graph, it can be noted that when $l_2,\ l_3 = 600$ (mm), the trajectory is always above the supporting plane. While with other pairs of inputs, the trajectory would intersect with the supporting plane. That means the robot leg may collide with the ground. So, we can conclude that when the main chain is uncontrollable, the broken leg is tolerable. Here, $l_2,\ l_3 = 600$ (mm) is one pair of inputs that could guarantee the robot leg not touch the ground.

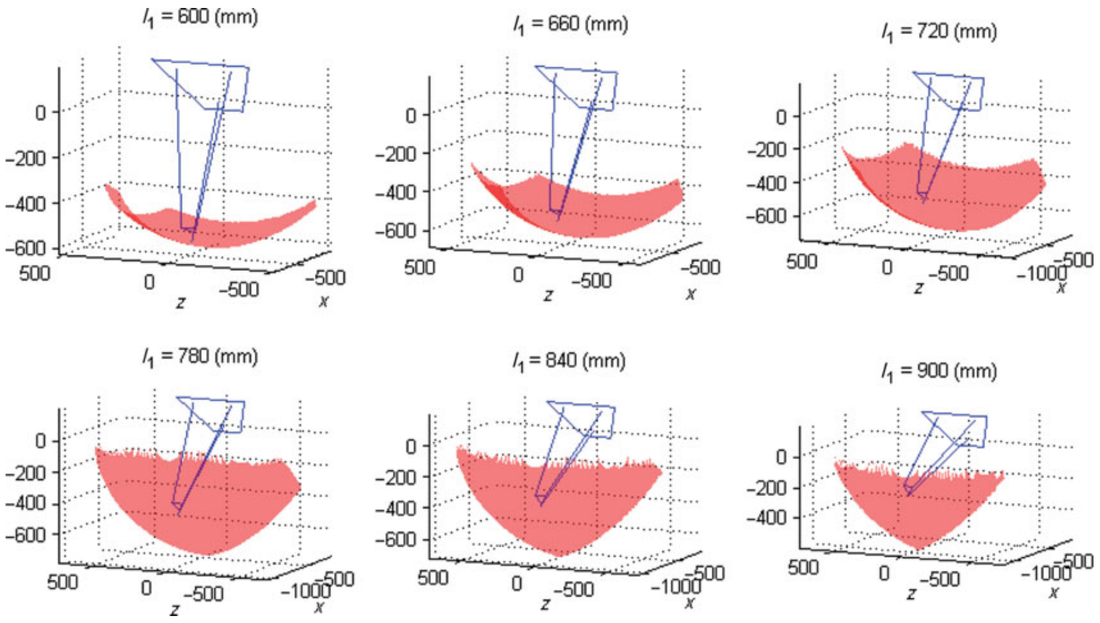


Fig. 5. Subspaces when l_1 locked at different *s*.

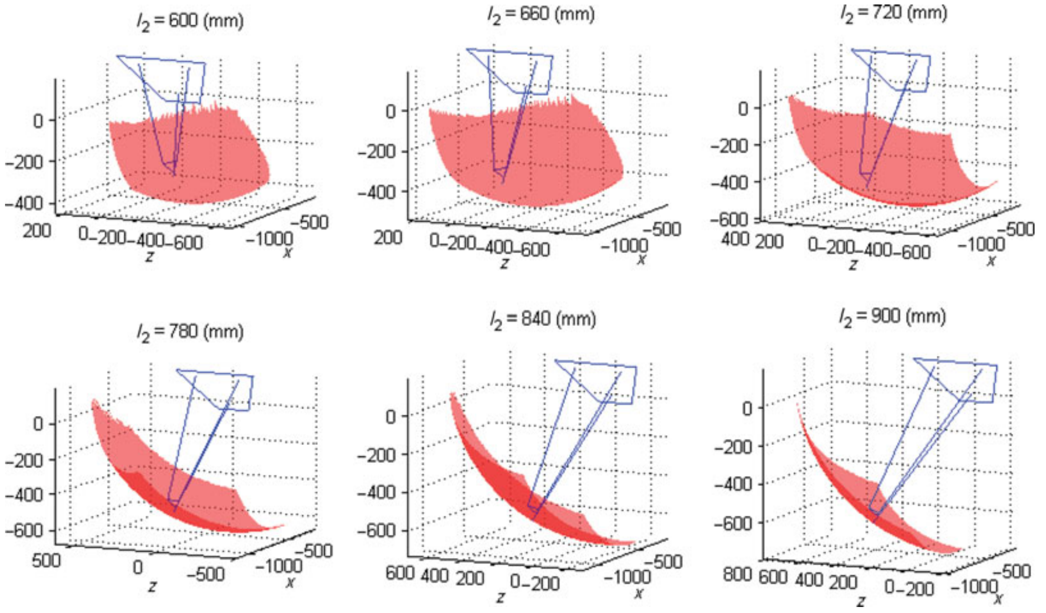


Fig. 6. Subspaces when l_2 locked at different *s*.

The fault-type $A_N B_U B_N$ can be analyzed in the same way. Figure 8 shows the EE trajectories when one assistant chain l_2 lost its control, with different inputs l_1 and l_3. From the graph, it can be noted that, when $l_1,\ l_3 = 600$ (mm) or $l_1,\ l_3 = 700$ (mm), the foot trajectories are always above the supporting plane. In conclusion, while only one assistant chain of a broken leg is uncontrollable, the leg is tolerable. Some feasible inputs are: $l_1,\ l_3 = 600$ (mm) and $l_1,\ l_3 = 700$ (mm).

Synthesizing all these analysis, we know that the four combinations of only one actuator fault are all tolerable.

4.3. Broken leg with more faults

When a faulted leg has more than one fault, the fault tolerance becomes much more complex than those with one fault. For those broken legs with more than two uncontrollable faults, the leg random

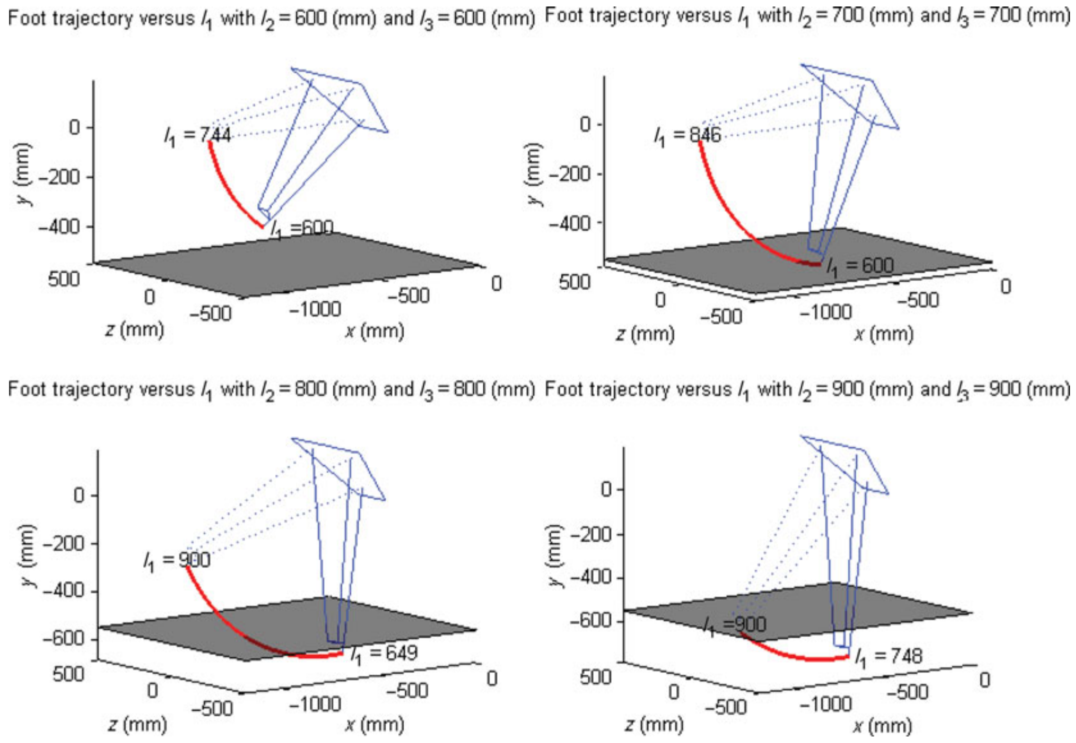

Foot trajectory versus l_1 with l_2 = 600 (mm) and l_3 = 600 (mm)
Foot trajectory versus l_1 with l_2 = 700 (mm) and l_3 = 700 (mm)
Foot trajectory versus l_1 with l_2 = 800 (mm) and l_3 = 800 (mm)
Foot trajectory versus l_1 with l_2 = 900 (mm) and l_3 = 900 (mm)

Fig. 7. Trajectories of main chain uncontrollable.

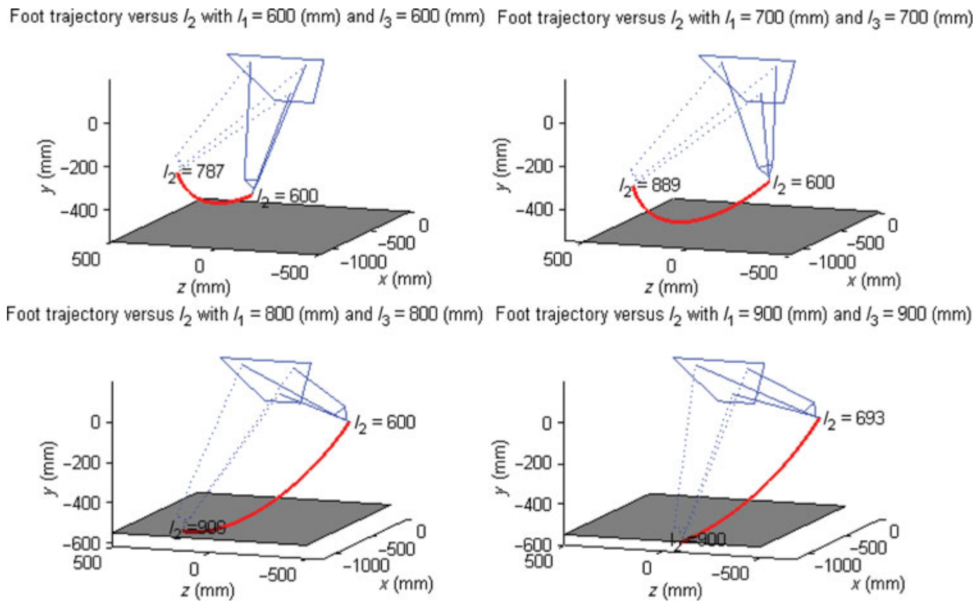

Foot trajectory versus l_2 with l_1 = 600 (mm) and l_3 = 600 (mm)
Foot trajectory versus l_2 with l_1 = 700 (mm) and l_3 = 700 (mm)
Foot trajectory versus l_2 with l_1 = 800 (mm) and l_3 = 800 (mm)
Foot trajectory versus l_2 with l_1 = 900 (mm) and l_3 = 900 (mm)

Fig. 8. Trajectories of assistant chain uncontrollable.

swing spaces become curved surfaces, which obviously interfere with the ground. Thus, these kinds of fault combinations are treated as intolerable. Such combinations include: $A_U B_U B_U$, $A_N B_U B_U$, $A_U B_U B_N$, $A_L B_U B_U$, and $A_U B_L B_U$.

For broken legs with less than two uncontrollable faults, the fault tolerance is dependent on the locked positions. If the locked chains are too long (near $l_{\max}$), the legs may be intolerable, if they are near $l_{\min}$, the legs are more likely to be tolerable. The fault combinations that are dependent on the locked positions include: $A_N B_L B_L$, $A_L B_L B_N$, $A_L B_U B_N$, $A_U B_L B_N$, $A_N B_L B_U$, $A_U B_L B_L$, $A_L B_U B_L$, and $A_L B_L B_L$.

Thus, the fault tolerance of a single leg can be divided into three groups: (1) if the leg contains one fault, the leg is tolerable; (2) if the leg contains more than one uncontrollable fault, the leg is intolerable; (3) otherwise the tolerance depends on the locked positions.

5. Analysis of Robot with Failure

5.1. *Fault types of robot*

Faults may occur to different legs when there are more than one fault in the robot. The robot needs at least four normal legs to maintain static walking gait, thus there should not be more than three faulted legs. That is to say the maximum possible number of actuation faults in a tolerable situation is six. Since the robot is isotropic in six leg directions and these six legs are exactly the same in structure, it makes no difference if there is only one broken leg. If there are two broken legs, the relative position of these two legs may affect robot fault tolerance. There are three possibilities: these two legs are adjacent, opposite, or neither adjacent nor opposite. Besides, fault number, fault types, and fault positions also influence the robot fault tolerance. Therefore, all fault possible combinations of the robot should be discussed.

Table II calculates all possible robot fault combination numbers when less than two legs failed. It is not necessary to explain all the formulas and here only take the four faults situation as an example to explain the analysis method further. When the robot has four faults, these four faults must occur in two different legs. If one faulted leg has one fault and the other has three faults based on analysis in Section 3, the 1-fault leg has $C(1, 4)$ combinations and the 3-faults leg has $C(1, 6)$ combinations. So the possible combination number of 1-fault leg and 3-faults leg is $C(1, 6) \cdot C(1, 4)$. If each leg has two faults, if the two legs have the same fault types, the possibility is $C(1, 7)$; else if the two legs have different fault types, the possibility is $C(2, 7)$. Thus, for these 2-fault legs, the combination number is $C(2, 7) + C(1, 7)$. Considering there are three types of relative position of the two broken legs: adjacent, opposite, and neither adjacent nor opposite, the total types of four faults can be calculated as follow:

$$S_R = C(1, 3) \cdot [(C(2, 7) + C(1, 7)) + C(1, 7) \cdot C(1, 4)] = 156 \tag{8}$$

which shows that, with four faults, the robot has 156 faulted combinations. In the same way, we can calculate the types of the robot with the number of faults from one to six.

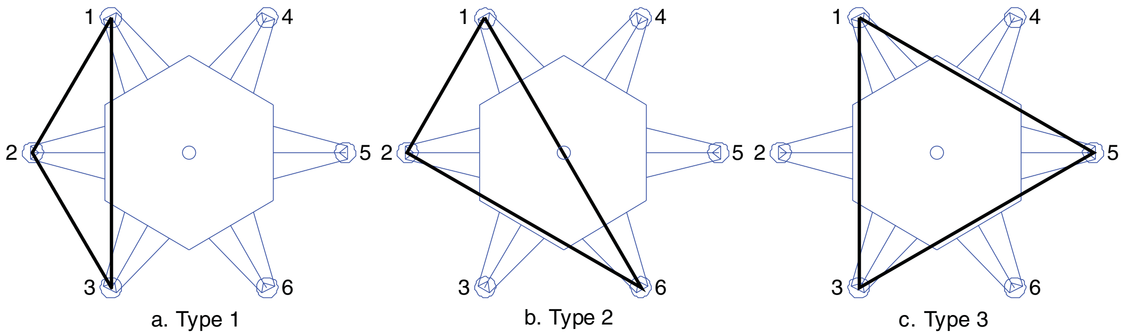
According to Table II, the total combination number is 476 when the robot has less than two faulted legs, but it is impossible to analyze every situation in this paper. From Table I, it is known that only four combinations are definitely tolerable, while others are either dependent on the locked positions or intolerable, and in this paper, only these four tolerable combinations are discussed: $A_U B_N B_N$, $A_L B_N B_N$, $A_N B_L B_N$, and $A_N B_U B_N$.

5.2. *Supporting triangle*

For isotropic hexapod robots, there are totally three kinds of supporting triangles. Figure 9(a) shows type 1 that is the best because the COG is inside the triangle and static stability margin (SSM) is the largest. For type 2 as in Fig. 9(b), although the COG lies on one of the triangle borders and SSM equals to zero, the robot still can walk by adjusting its body posture and supporting feet positions during its gait planning process. When the robot uses triangles of type 3 as in Fig. 9(c), the COG is too far from its static stable area, and the robot will definitely fall. Thus, type 3 must be avoided while walking.

5.3. *Robot with one tolerable leg*

Figure 10 illustrates the robot standing posture with one faulted leg of top view. All six legs are distributed evenly around the body and COG is near the center of the body. Normal legs are on the ground supporting the robot, which are drawn by solid lines. The broken leg must lift off the ground and cannot support robot body any more, which is drawn by dashed lines in the figure. The polygon drawn by black lines is the biggest supporting area. As we can see from Fig. 10, when the robot lifts leg 1, remaining legs can form 2–3–5, 2–3–6, 2–5–6, and 3–5–6 supporting triangles of type 2. When lifting leg 2, the remaining legs can form 1–3–5 supporting triangle of type 1, or 1–3–6 and



a. Type 1 b. Type 2 c. Type 3

Fig. 9. Supporting triangles of the robot.

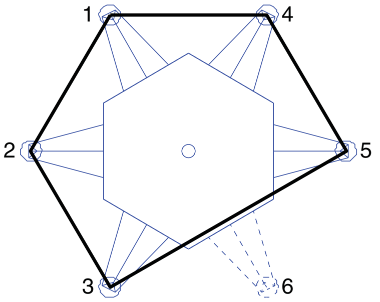
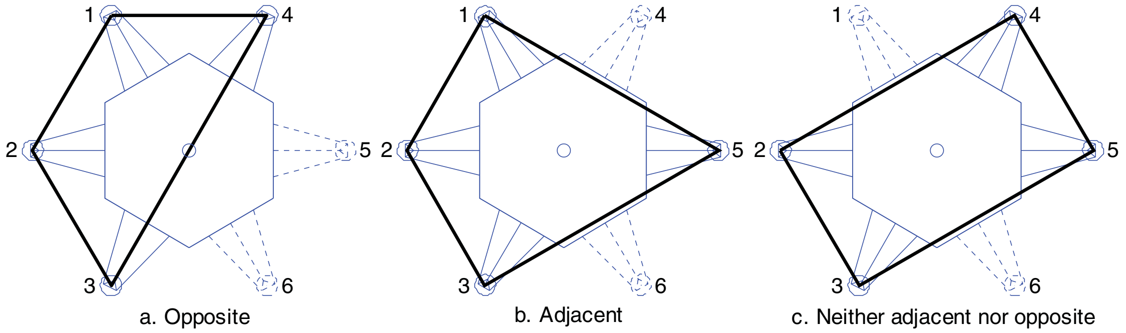


Fig. 10. Robot with one broken leg.



a. Opposite b. Adjacent c. Neither adjacent nor opposite

Fig. 11. Robot with two broken legs.

3–5–6 supporting triangles of type 2. When lifting other legs, the situations are similar to lifting leg 1 or 2. Thus, no matter which leg is to be lifted, feasible supporting triangles can always be found. In conclusion, when there is only one tolerable leg, remaining legs can always make supporting triangles of type 1 or type 2. Therefore, the robot is able to use static stable gait to walk with only one tolerable leg.

5.4. Robot with two tolerable legs

Three different combinations with two tolerable broken legs are drawn in Fig. 11. When two tolerable legs are opposite as in Fig. 11(a), no matter which normal leg is to be lifted, supporting triangle will always be type 2. If two adjacent legs are broken, as in Fig. 11(b), lifting leg 6 will cause the supporting triangle to be type 3, which is not permitted. The same thing will happen in Fig. 11(c), when two tolerable legs are neither adjacent nor opposite. This time the supporting triangle will become type 3 when lifting leg 5. In a word, the robot cannot walk when two tolerable legs are not opposite.

Finally, based on above analysis, the robot can definitely walk with one tolerable leg or two tolerable legs in opposite locations.

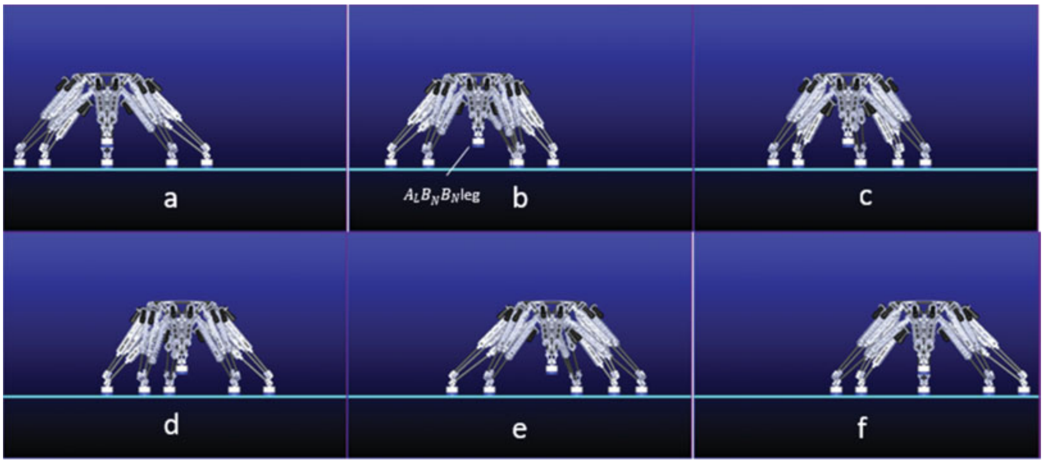


Fig. 12. Robot walking with one tolerable leg.

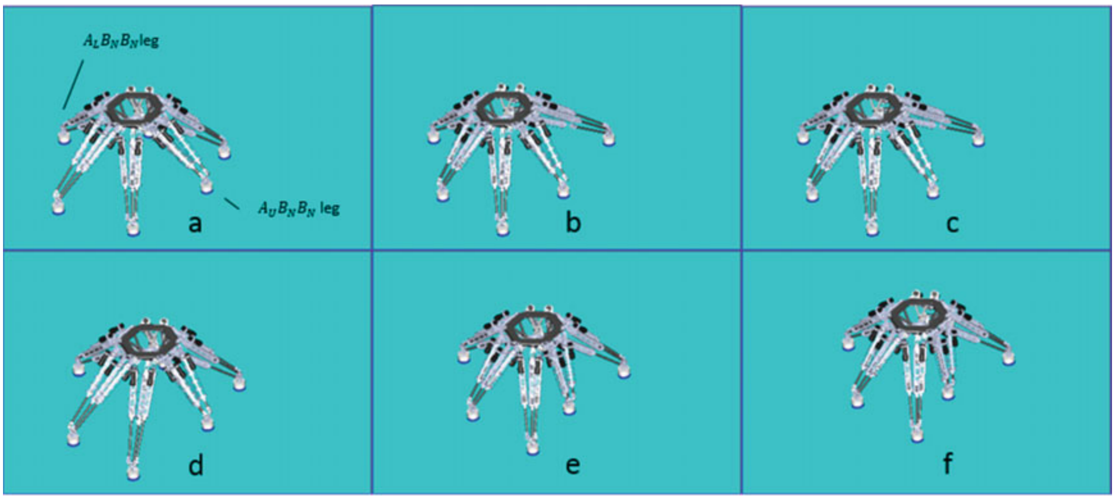


Fig. 13. Robot with an $A_L B_N B_N$ leg and an $A_U B_N B_N$ leg.

6. Simulation

Relative dynamical simulations have been done for both one and two broken legs. With one or two broken legs, the robot can walk successfully in the simulation environment. If there exist one faulted leg, the robot could use 2–2–1 gait, which means in a walking period first the robot moves 2 legs forward, then moves another 2 legs, then the last 1 leg, and finally it moves its body. In the whole walking process, the COG is always inside the supporting triangle to keep the robot stable. When two opposite leg are faulted, the robot would use static gait and walks like a quadruped robot: each time it only moves one leg and finally it moves its body.

Figure 12 shows the robot walking with one $A_L B_N B_N$ tolerable leg. The main chain of the broken leg was locked at 620 mm position. In the simulation, inputs of l_2 and l_3 were all set to 620 mm. With this pair of inputs, the broken leg foot tip was at 401 mm. Then, the robot could successfully walk with the other five normal legs. In the whole walking process, the broken leg was always above the ground as shown in the picture.

Figure 13 illustrates the robot walking simulation with two broken legs, which located at opposite positions. One of them was $A_U B_N B_N$ and the other one was $A_L B_N B_N$. The main chain of the $A_U B_N B_N$ leg main chain was locked at 620 mm, and again l_2 and l_3 were set to 620 mm, which could guarantee the foot tip above the ground. For the $A_U B_N B_N$ leg, since the main chain was uncontrollable, thus the foot would drop down due to gravity. l_2 and l_3 were set to 600 mm which could make the foot tip trajectory always above the ground according to analysis in Section 4.

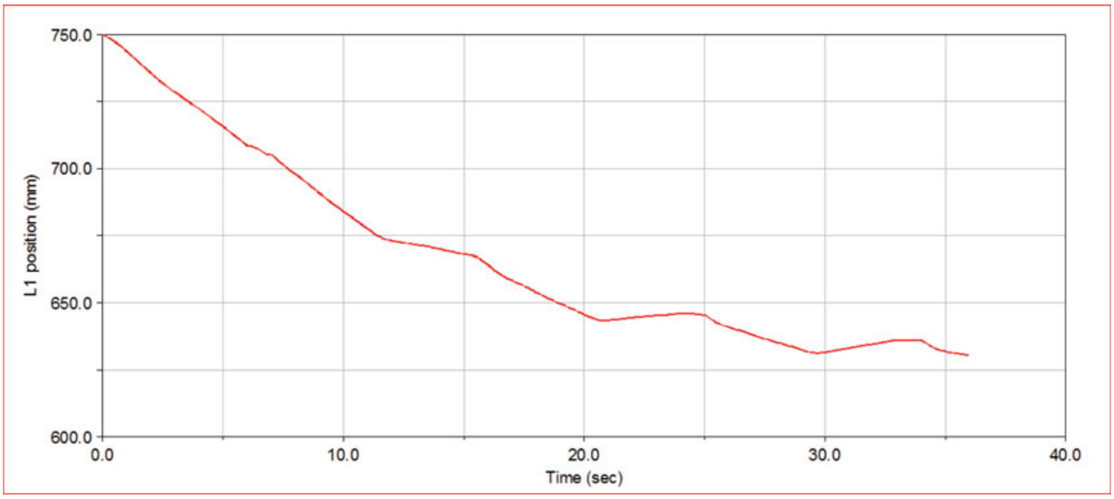


Fig. 14. Uncontrollable main chain position.

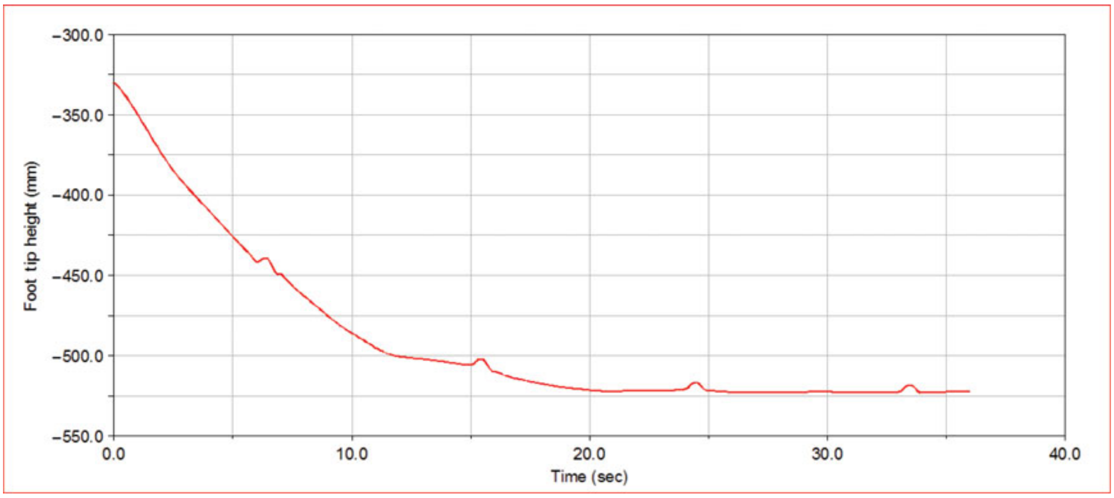


Fig. 15. Foot tip height.

With the remaining four normal legs, the robot could walk with static stable gait. In the simulation process, the uncontrollable motor moved freely, which leaded to the foot tip swing randomly. Figure 14 shows the main chain position of uncontrollable motor. Figure 15 shows the foot tip height during the walking process. Apparently the robot leg was always higher than the ground.

7. Conclusion

In this paper, fault tolerance of a parallel–parallel hexapod walking robot is analyzed. So far to the best knowledge of the author, no scholar has ever analyzed broken-leg effects to the robot, and most of previous research simply treated the broken leg not existent or not able to move. In our work, the robot fault tolerant capability is analyzed by actuation fault types together with the robot leg mechanism. A leg tolerance criterion is proposed and if the broken leg could fall to the ground, the robot is regarded to be faulted. If two legs are faulted, the broken leg positions’ effect to the robot walking capability is discussed.

The conclusions can be summarized as follows:

1. Two types of robot actuation faults are defined: locked faults and uncontrollable faults.

2. A criterion of leg fault tolerance is brought out. There are totally 17 fault combinations for a single leg, while four of them can be definitely tolerated, five of them are intolerable, and remaining types are dependent on the chain-locked positions.
3. If the robot is tolerant with faults, two conditions should be satisfied: (a) all faulted legs must be tolerable, and (2) less than three legs are faulted and if two legs are faulted, they must be opposite.

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