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R-Crank: Amphibious all terrain mobile robot

Shintaro Yamada[1], Shigeo Hirose[2], Gen Endo[1], Koichi Suzumori[1] and Hiroyuki Nabae[1]

***Abstract*— An amphibious all terrain mobile robot is required for disaster response tasks. In this paper, we propose ”R-Crank” , which has simple four wheels driving configuration with crank links, connecting to ipsilateral front and rear wheel so as to form parallel four-bar linkage systems.The crank links act as legs because their trajectory with respect to the ground become trochoid curve, which is commonly used as leg trajectories for a legged robot. These links achieve high terrain adaptability while maintaining simple structure of the wheeled robot. We developed a prototype model and carried out basic experiments. The robot achieved to climb 0.3 m of a step(76.9 % of wheel diameter), stairs and a snowy slope. In addition, we propose amphibious structure of crank links by installing multiple rigid paddles. The propulsive force generated by the crank links was measured and empirically derived the optimum parameters by using small-sized experimental apparatus. Finally the robot equipped with the amphibious crank links achieved propulsion on water at 0.13 m/s. We also verified that the robot achieved going up and into water through stairs.**

I. INTRODUCTION

In the case of the disaster such as earthquake, tsunami, landslide caused by torrential rain disaster, it is important to gather information of the affected areas accurately and quickly. Mobile robots which have high mobility, dust proof and water proof are required to prevent secondary disaster.

Generally speaking, robots for disaster response are classified into three categories, legged robots, tracked robots and wheeled robots. Although a legged robot is potentially capable of high mobility on rough terrain, its energy efficiency in locomotion is low and maximum payload is limited[1][2][3]. A tracked robot has high mobility on rough and/or deformable terrain such as bog and snow thanks to its large ground contact area. However, it is difficult to increase reliability in disaster site because there are many hard debris and string shape metal wires which are easily caught between sprockets and tracks. Moreover, it is also difficult to seal all sliding members to avoid these debris, and sealing may decrease energy efficiency of locomotion, due to the resistance of the seals[4][5]. A wheeled robot can run at high speed on flat and hard terrain, and have high energy efficiency, however locomotion capability on rough terrain is still limited. In order to improve mobility of a wheeled robot on rough terrain, many attempts have been done such as changing the material of the wheel, suspension and mechanism[6][7].

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Fig. 1: Overview of “R-Crank”

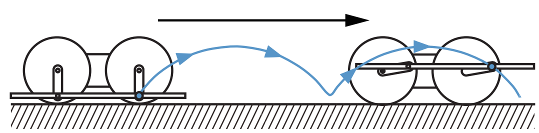


Fig. 2: Trochoid curve: trajectory of crank-legs

To increase locomotion capability of a wheeled robot, we have proposed ”crank-wheel” mechanism[8]. The crank-wheel mechanism consists of four driving wheel and crank links. Ipsilateral wheels rotate in the same speed, and the crank link is connected to the front and rear wheel at eccentric position with rotational joints in order to form four-bar parallel linkage. On smooth surface, the crank-wheel robot moves like conventional wheeled robot using wheels. On rough terrain, the crank-wheel robot exploit walking like movement of the crank link in order to get out of stuck (Fig. 2). The crank-wheel mechanism has high terrain adaptability while maintaining simple structure.

In this paper, we developed crank-wheel mechanism robot, ”R-Crank(Rover-Crank)” (Fig. 1) to improve our previous prototypes. Moreover, we discuss amphibious locomotion capability using the crank link by optimizing link structure for paddling.

The rest of paper is organized as follows. Section II introduces basic feature of crank-wheel mechanism, and Section III proposes a new crank-wheel mobile robot ”R-Crank”. The basic mobile experiments are reported in Section IV. The propulsion using crank link is investigated in Section V, and its experimental verifications are discussed in Section VI. Section VII concludes this paper and discusses future works.

II. CRANK-WHEEL MECHANISM

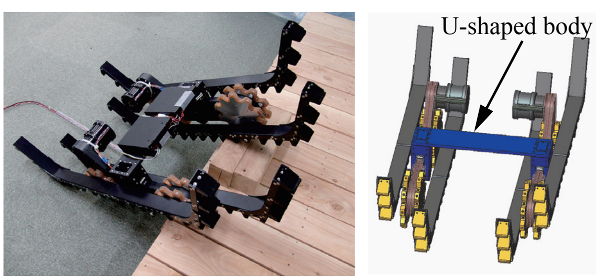
The crank-wheel mechanism is based on four-wheel drive mechanism which has high mobility on flat terrain. This mechanism can achieve steering by controlling rotational velocity of the left-and-right wheels. The characteristic point of this mechanism is four-bar parallel linkages connected to wheels. One of these links (call this link as “crank-leg” hereinafter) draw a trajectory of trochoid curve which is often used as leg trajectory of walking robot. On flat and hard terrain, the crank-leg does not work at all because length of crank-legs’ eccentricity is shorter than radius of the wheel. Thus the robot produces energy efficient locomotion using conventional wheels.

On soft deformable terrain or rough terrain, the crank-leg pushes the ground by increasing its ground contact area and prevent the robot from stuck. In addition, the robot can go through a high step and stairs using crank-legs.Furthermore, the wheel shafts are only sliding surfaces which are required to seal for dust proof and water proof owing to its simple mechanism.

In our previous work as shown in Fig. 3a, crank-wheel robot [8] had already been developed as a prototype. This model has curved crank-legs to reach high step, and keeps its dynamic balance by equipping two crank-legs for each sides at opposite phase. Thus four crank-legs are installed. This mechanical design forces to the body structure in a U-shape (Fig. 3b), making the body structure complicated and weak. Additionally, the wheel radius is not sufficiently large enough, and thus locomotion capability with wheels is low.

III. CONCEPT OF CRANK-WHEEL ROBOT “R-CRANK”

Based on the previous prototyping, we propose a new crank-wheel robot ”R-Crank”. R-Crank has large diameter drive wheels and a crank-leg is installed in one side. The main body has box structure. The basic features are followings.



(a) Overview of “crank-wheel” (b) U-shaped-body

Fig. 3: Crank-wheel robot “crank-wheel”[8]

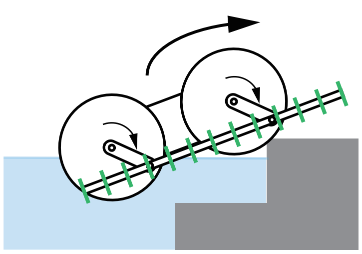


Fig. 4: Concept of movement when “R-Crank” gets out from water

- Simple and rigid body structure.
- Improved wheeled locomotion capability.
- Amphibious locomotion capability.

In order to simplify the mechanical structure, first we tried to reduce number of crank-legs (Fig. 5). We removed inner side crank-legs and did a stair climbing experiment using the previous prototype. It is confirmed that there is no significant difference between crank-wheel mechanism which has four crank-legs and two crank-legs, by an experiment on rough terrain and stairs (Fig. 6). Based on this result, four crank-legs were reduced to two. Since inner crank-legs are not installed, we can make high rigidity main body with box structure.

Furthermore, the mobility with its wheels was improved by increasing the diameter of the wheels. In addition, by lengthening eccentricity of crank-legs, height of a step which the crank-legs can reach became higher. Therefore we adapt simple and straight shaped crank-legs. The comparison of specification between “crank-wheel” and “R-Crank” is shown in Table I.

Additionally, we introduce the mobility of crank-wheel mechanism on water. Research of this kind of amphibious mechanism mainly direct to legged robot [9][10]. The amphibious crank-wheel mechanism can go on water using the movement of crank-legs by equipped with paddles without additional actuators. Thanks to the box structure of the main body, it is easy to adjust buoyancy force. Although this propulsion on water needs to match the waterline and axis of wheel, shallow water line provides advantage when the robot gets out from water as shown in Fig. 4 shows. Also, this mechanism can go through at any water depth since this mechanism uses same locomotion on ground and water. We do not consider the addition of degree of freedom for crank-leg’s active deformation to keep its simple mechanism.

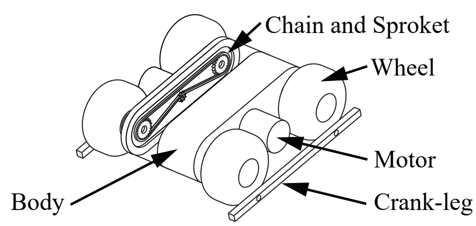


Fig. 5: Structure of “R-Crank”

TABLE I: Comparison of specification between “crank-wheel” and “R-Crank”

Parameter	Crank-wheel	R-Crank
Length	1.1-1.2 [m]	1.0 [m]
Height	0.31-0.37[m]	0.46 [m]
Width	0.59 [m]	0.72 [m]
Weight	28 [kg]	52 [kg]
Wheel diameter	0.2 [m]	0.39 [m]
Wheel base	0.4 [m]	0.51 [m]

Fig. 6: Climbing up stairs with only two crank-legs using "crank-wheel"

IV. MOBILITY ON THE GROUND

In this section, we did locomotion experiments on the ground to demonstrate basic performance of R-Crank. We install 22 spikes at 0.1 m intervals for the crank-legs in order to achieve high thrusting force.

A. Step

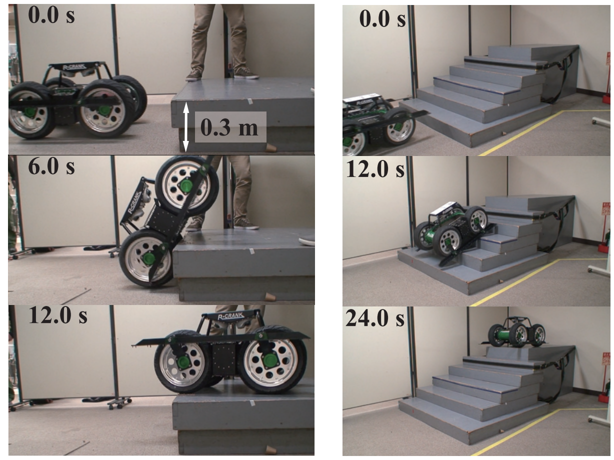
R-Crank achieved to climb a step of which height is 0.30 m which is impossible without clank-legs (Fig. 7a). The height of the step is 76.9 % of the diameter of wheels which are 0.39 m. In case of experiment without crank-legs, the front wheels could climb the step but the rear wheels could not. The maximum height of crank-legs from the ground is 0.31 m which is almost the same as the height of the step. This experiment shows that it is possible to climb up a step for the robot as long as crank-legs catch the step.

B. Stairs

In the experiment of stairs, the robot also achieved to climb up the stairs (Fig. 7b): The tread of the steps of the stairs is 0.15 m, and the rise of the step is 0.27 m. When the robot climbs up the stairs, crank-legs work as if it is walking. The robot can climb only one step of the stairs in one revolution. The phases of crank-legs can be controlled by slipping the wheels on stairs although match of the phases of crank-legs is need in order to climb stairs.

C. Snowy terrain

It is difficult to go through snowy terrain for robots, because of its low friction coefficient and softness. As shown in Fig. 8, an experiment was carried out on snowy terrain. The robot did not get stuck on snow by using wide ground contact area of clank-legs. In this experiment, the robot also achieved to climb up snowy slope of which inclination is 15°.



(a) Climbing a step (b) Climbing stairs

Fig. 7: Experiments on ground

Fig. 8: Experiment on snowy terrain

V. ANALYSIS FOR MOBILITY ON WATER

In order to introduce propulsion mechanism on water, most straight forward solution is to use a screw. However additional actuator is required and it is not used on the ground. Paddles would be a good solution to generate thrusting force without additional actuator. Paddles can be arranged radially beside wheels and also attached to the crank-legs. Since radial arrangement of paddles obviously generates thrusting force assuming constant angular velocity of the wheel, we focus on installing paddles on the crank-leg in this paper. We develop experimental apparatus to measure fluid force acting on the crank-leg when it is completely under water. After empirically deriving the optimum number of paddles and shape of the crank-leg, we determine appropriate waterline in order not to generate drag force by adjusting buoyancy.

A. Experimental Apparatus

We designed and fabricated an experimental apparatus which is 1/2 scale of R-Crank (Fig. 9) in order to measure the force which is generated from fluid. The experimental apparatus is composed of a drive module, a force gauge module and a crank-leg. The force of propulsive direction and vertical direction can be measured by a force gauge module. The crank-leg is put completely in static water during the experiment, and rotated at constant speed. We do not consider the effect of the water flow. The fluid force F_x and F_z are the value which subtract centrifugal force of the crank-leg from measured values. This centrifugal force is calculated from rotational speed measured from a motor

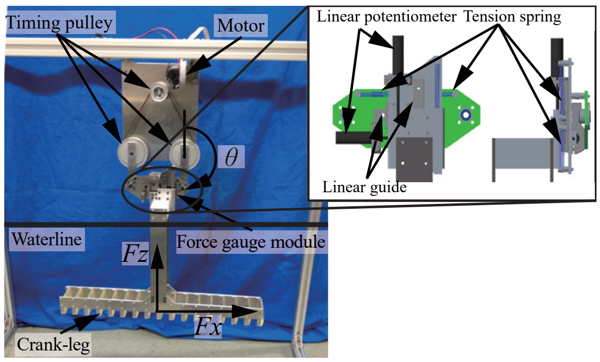


Fig. 9: Overview of experimental apparatus

encoder and mass of the crank-leg. We determine appropriate waterline in order not to generate dragging force by adjusting buoyancy.

B. Experiments

The experiments were executed using the experimental apparatus. In these experiments, the angle of crank-leg's phase θ is defined as 0° when it is top, and its positive direction is the same direction as the wheels' rotation when the robot goes forward.

1) Rotational speed: We carried out experiments to elucidate how the fluid force of propulsion direction F_x depends on the rotational speed ω. Relationship between F_x and phase of the crank-leg θ is shown in Fig. 10, and force amplitudes A_{Fx} were calculated by fitting sine function using least squares method through following equation.

$$F_x \approx A_{Fx} \sin(\theta - \beta). \tag{1}$$

Equation of lift force L and drag force D from fluid can be written by coefficient of lift C_L and coefficient of drag C_D.

$$\begin{pmatrix} L \\ D \end{pmatrix} = \frac{1}{2}\rho U^2 S \begin{pmatrix} C_L \\ C_D \end{pmatrix}, \tag{2}$$

where the density of the fluid, the relative speed of the fluid and the representative area are ρ, U and S, respectively. Taking account of the equation, it is reasonable to assume that the fluid force is proportional to the square of the relative speed, that is to say, the fluid force from crank-leg is proportional to rotational speed of crank-leg. Fig. 11 shows the calculated force amplitude and its approximate curve, and shows that force amplitude and approximate curve are nearly equal. This approximation curve is obtained by approximating the square of the rotational speed. As a result of this experiment, following equation can be obtained as

$$F_x \propto \omega^2. \tag{3}$$

2) Number of paddles: We calculated force amplitude A_{Fx} in the same way of analyzing for the rotational speed (Fig. 12). Although adding the number of paddles increases the fluid force in the range of the experiment, force per one paddle is decreased. If number of paddles increases, force amplitude is expected to decrease because distance between paddles are narrow and water does not flow between paddles. However, the expected decrease is not observed in feasible hardware range. Taking into account the dynamic balance of the robot, it is preferable for robot that the weight of the crank-legs are light. As a result, we adopt 17 paddles for crank-legs.

3) Three-dimensional (3D) shaped paddles: The relative velocity of crank-legs to the body is characterized by sine function. Therefore, energy loss causes since virtual mass (mass of water accompanied with crank-leg) repeats acceleration and deceleration. In order to reduce this energy loss, we designed three-dimensional shaped paddles: The paddles are bended, and side plates are holed (Fig. 13a). The aim of this 3D shape is to avoid deceleration of the virtual mass because the virtual mass passes through the inside holes. For comparison, we prepared three paddles as Fig. 13b and Fig.

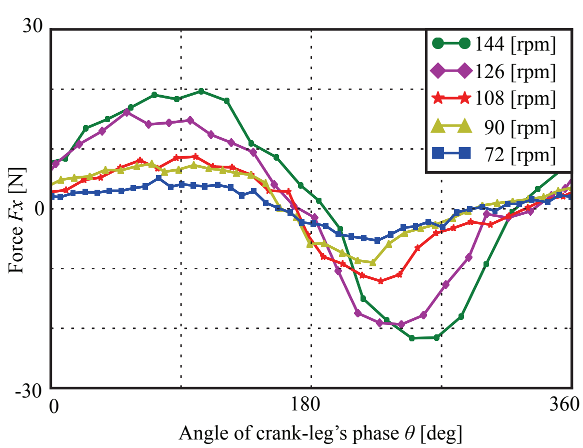


Fig. 10: Relationship between the angle of crank-leg's phase θ and fluid force F_x in each rotational speed: Number of paddles is 9.

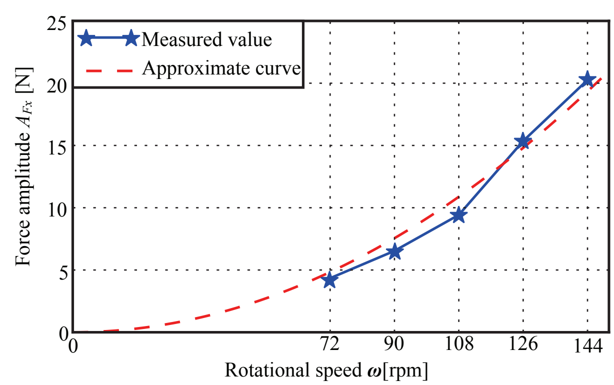


Fig. 11: Relationship between rotational speed and force amplitude A_{Fx} : Number of paddles is 9.(blue line is measured value, red line is approximated by constant multiple of square of rotational speed.)

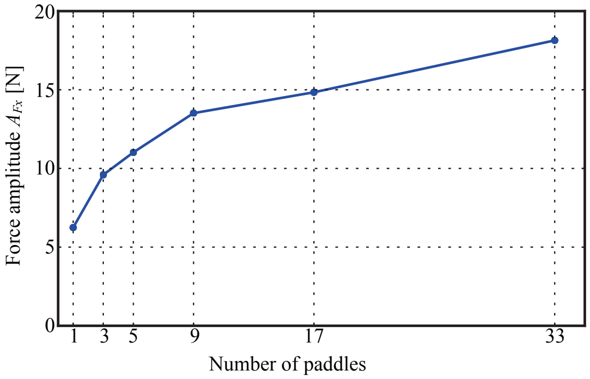
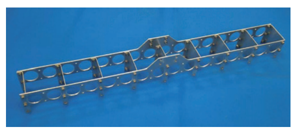
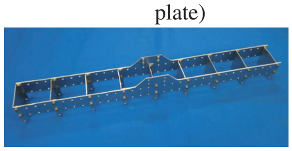


Fig. 12: Relationship between number of paddles and force amplitude A_{Fx} where rotational speed is 108 rpm.

(a) Type A (with hole, bended plate)



(b) Type B (with hole, straight plate)



(c) Type C (without hole, straight plate)

Fig. 13: 3D shaped crank-legs

13c shows. As a result, negative force was reduced as we expected (Fig. 14).

C. Estimates of speed on water

We estimated the propulsive velocity of the R-Crank on water by using the result of analysis. In this estimate, we assume that degree of freedom of the robot is only in propulsive direction, and propulsion due to the wheels rotation is not taken into account. The force which the robot receives are fluid force F_x from crank-legs, centrifugal force of crank-legs and drag force of the robot. This F_x is converted from the experimental value in accordance with Equation 3, and is 0 N when the crank-legs are out of water. We discuss the case where the phase of crank-leg is opposite. In such case, centrifugal force of crank-legs are canceled each other. We define symbols as shown in Table II: Coefficient of drag C_D includes coefficient of wave drag. A motion equation about the propulsive direction is shown as follows.

$$\frac{d}{dt}(MU) = F_x - \rho U|U|WH_{\text{water}}C_D. \tag{4}$$

Using the equation and the result of experiments, we estimated the robot's speed on water (Fig. 15). When the time t is 0 s, the initial speed of the robot $U|_{t=0}$ is 0 m/s. Terminal average speed is calculated as 0.187 m/s.

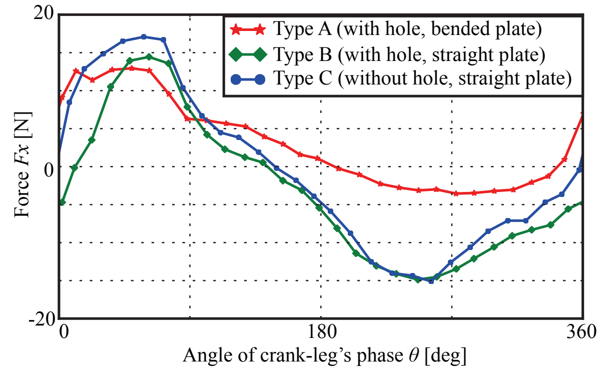


Fig. 14: Relationship between the angle of crank-leg's phase θ and fluid force F_x in each 3D shaped crank-legs: Number of paddles is 9, and rotational speed is 108 rpm.)

TABLE II: Definition of symbols

Parameter	Symbol	Value
Mass	M	52 [kg]
Speed	U	- [m/s]
Density of water	ρ	1000[kg/m^3]
Height in water	H_{water}	0.19 [m]
Width	W	0.72 [m]
Coefficient of drag	C_D	3.0
Time	t	- [s]

VI. Experiment on water

Demonstrations for amphibious crank-wheel mechanism were carried out at a river where its riverside is stairs. Based on the result of scale model experiment, we designed crank-legs for amphibious mechanism shown in Fig. 16. The crank-legs have seventeen paddles, and adopt proposed 3D-shape. Also, we adopted inclined paddles of which angle is 30°. Although reduction of the fluid force is assumed when θ is around 90° because paddles' angle of attack is minus, increase of the fluid force is assumed when θ is around 270° conversely. As a result, the fluid force is averaged to decrease the energy loss and reduce change of speed.

R-Crank equipped with the amphibious crank-legs (Fig. 17) achieved the speed of 0.13 m/s on water, and succeeded entering to water, and getting out from water through the stairs using the same locomotion method (Fig. 18), where

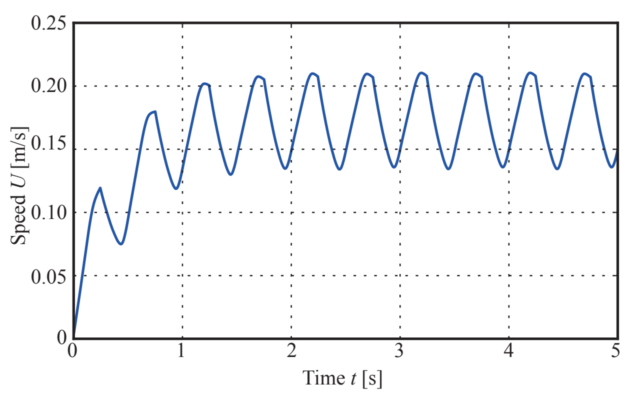


Fig. 15: Simulation of the speed of the robot on water

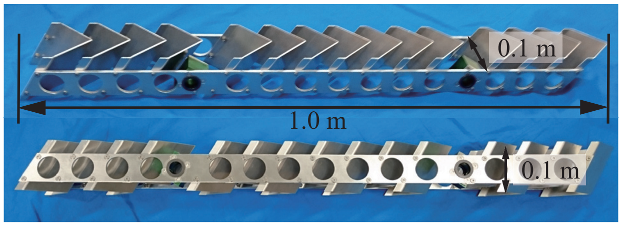


Fig. 16: Overview of designed amphibious crank-leg

Fig. 17: “R-Crank” equipped with the amphibious crank-legs

the run of a step of the stairs is 0.25 m, and height of the step is 0.49 m. In addition, the robot succeeded backward locomotion and pivot turn to show the mobility in narrow space on water. The difference of speed between the experiment and estimation might be caused by the ignored effect of water flow.

VII. CONCLUSIONS AND FUTURE WORK

An amphibious all terrain mobile robot “R-Crank” was proposed and verified its performance by a hardware prototype in this paper. In the mobility experiment on the ground, the robot achieved to climb a step of which height is 0.3 m (76.9 % of wheel diameter), stairs and a snowy slope. In addition, we proposed amphibious mechanism using crank-wheel mechanism. We developed the mechanism based on result of scale model experiment. The robot equipped with the amphibious mechanism achieved propulsion on water at 0.13 m/s, going up and into water through stairs, pivot turn and backward movement.

Comparison of cost of transport on various terrain and experiments using the amphibious crank-legs on ground are remained as future works,

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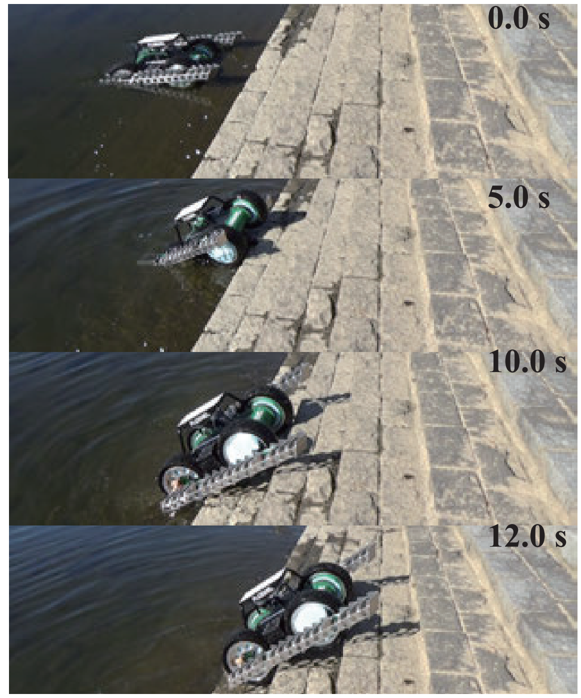

Fig. 18: Movement when “R-Crank” gets out from water

REFERENCES

[1] M. Raibert, K. Blankespoor, G. Nelson, R. Playter, and T. Team, “Bigdog, the rough-terrain quadruped robot,” in *Proceedings of the 17th World Congress*, vol. 17, no. 1, 2008, pp. 10 822–10 825.

[2] C. Semini, N. G. Tsagarakis, E. Guglielmino, M. Focchi, F. Cannella, and D. G. Caldwell, “Design of hyq–a hydraulically and electrically actuated quadruped robot,” *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, p. 0959651811402275, 2011.

[3] S. Kitano, S. Hirose, G. Endo, and E. F. Fukushima, “Development of lightweight sprawling-type quadruped robot titan-xiii and its dynamic walking,” in *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*. IEEE, 2013, pp. 6025–6030.

[4] K. Nagatani, S. Kiribayashi, Y. Okada, K. Otake, K. Yoshida, S. Tadokoro, T. Nishimura, T. Yoshida, E. Koyanagi, M. Fukushima *et al.*, “Emergency response to the nuclear accident at the fukushima daiichi nuclear power plants using mobile rescue robots,” *Journal of Field Robotics*, vol. 30, no. 1, pp. 44–63, 2013.

[5] B. M. Yamauchi, “Packbot: a versatile platform for military robotics,” in *Defense and Security*. International Society for Optics and Photonics, 2004, pp. 228–237.

[6] T. Aoki, Y. Murayama, and S. Hirose, “Mechanical design of three-wheeled lunar rover;“tri-star iv”,” in *Robotics and Automation (ICRA), 2011 IEEE International Conference on*. IEEE, 2011, pp. 2198–2203.

[7] H. Komura, H. Yamada, S. Hirose, G. Endo, and K. Suzumori, “Study of swing-grouser wheel: A wheel for climbing high steps, even in low friction environment,” in *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on*. IEEE, 2015, pp. 4159–4164.

[8] H. Nakano and S. Hirose, “Crank-wheel: A brand new mobile base for field robots,” in *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*. IEEE, 2012, pp. 4608–4613.

[9] A. S. Boxerbaum, P. Werk, R. D. Quinn, and R. Vaidyanathan, “Design of an autonomous amphibious robot for surf zone operation: part i mechanical design for multi-mode mobility,” in *Proceedings, 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*. IEEE, 2005, pp. 1459–1464.

[10] C. Prahacs, A. Saudners, M. K. Smith, D. McMordie, and M. Buehler, “Towards legged amphibious mobile robotics,” *Proceedings of the Canadian Engineering Education Association*, 2011.