DEVELOPMENT OF AUTOMATED SHORELINE SURVEYING SYSTEM USING AMPHIBIOUS WALKING ROBOT

- THE DESIGN CONCEPTS AND THE 1ST FIELD EXPERIMENT -

Toshinari TANAKA
Construction and Control Systems Department
Port and Airport Research Institute
3-1-1 Nagase, Yokosuka, Kanagawa, Japan
tanaka_t@pari.go.jp

Tetsuya SHIRAISHI
Construction and Control Systems Department
Port and Airport Research Institute
3-1-1 Nagase, Yokosuka, Kanagawa, Japan
shiraishi-t84mv@pari.go.jp

Abstract: One of the main work is survey work at shoreline in port areas. For instance, harbor-masters survey shorelines to maintain encroached beach, and some work are carried out on weak terrain. Consequently, the primary working force is still human-intensive although the mechanization is desired from viewpoint of the efficiency.

Therefore, we are on the studying automated shoreline surveying system using walking robot which does not damage the terrain seriously. And, we developed prototype robot which had some unique features. One is the same mechanism of all joints, and they are independent respectively to each other as watertight type joint units. Another one is that the legs and the body unit are able to be detached easily in case of maintenance.

In this paper, we describe in detail the design concepts and the features of the prototype robot applied moduled watertight structures, and report the 1st experimental result in the field.

Keywords: Shoreline survey work, Amphibious walking robot, Moduled watertight structure

1. INTRODUCTION

There are many characteristic waterside areas such as shoals or shorelines in the port areas. They are unique areas where there are both land and underwater areas. One of the main work is survey work at such waterside areas in port areas. For instance, the harbor masters survey the shorelines to maintain encroached beach. Tidal flats are also surveyed to monitor the environment and the ecosystem. Some of the survey work in the areas are carried out on weak terrain although the survey work with water depth margin are carried out by vessels. Consequently, the primary working force is still human-intensive although the mechanization and automatization are desired from view point of the efficiency. Moreover, this is attributed to the fact that it is difficult to use same method for surveying in land and water.

Therefore, we are on the studying of automated topographic survey work in waterside areas such as shoreline and developing automated surveying system. We consider that this is the same also in the waterside or underwater because walking machine does not damage the terrain seriously. We have verified the validity of the countermeasure suggested by us in the experiment on land [1].

Consequently, we developed prototype amphibious walking robot which had some unique features in the structure and composition in order to experiment our proposed method in real sea. One of the structural features is the same mechanism of all joints, and they are independent respectively to each other as watertight type joint units. This feature contributes to the simplicity of the composition of the robot. Another structural feature is that the legs and the body unit are able to be detached easily in case of the maintenance.

In this paper, the design concepts to consider the various work site conditions and the features of the prototype amphibious walking robot which applied moduled watertight structure is describe in detail as follows. And, the 1st field experimental result using the developed automated surveying system with amphibious walking robot in the field is reported where is Niigata West Coast. It is one of the coasts directly maintained by Hokuriku Regional Development Bureau. Because retreat of the sandy beach amounts to about 350 [m] at the maximum since 1947 although city area is located just behind the coast. The sand volume is managed by the administrative bureau as a part of the maintenance services, and a sand fill work is partly implemented.

2. METHODS FOR SHORELINE SURVEY WORK

2.1 Ordinary methods

Sea bottoms in port areas are usually surveyed using a working vessel with echo sounder from the view point of the efficiency. On the other hand, workers usually take levels between land and water areas such as shore line at present situation. At first, the workers perform longitudinal leveling in order to obtain exact benchmarks. Next, the workers perform cross-sectional leveling using the benchmarks in order to obtain the cross-section of the beach. Furthermore, the user should be attentive when the survey data with different accuracy acquired in a different method is connected mutually.

Figure 1. shows a present situation of regular shore line survey work which is cross-sectional leveling in Niigata

Figure 1. Regular shoreline survey work in Niigata West Coast (Cross-sectional leveling).

West Coast between land and water. Moreover, one of the workers walks into the water with a staff.

In this case, the workers take levels at intervals of 5 [m] on a cross-sectional survey path. And, the path is planed at intervals of 25 [m]. The method has accuracy of millimeter order and is more than enough.

2.2 A proposed method for automated survey work

A basic idea of the proposed method in this study is very unique because autonomous type prism man (survey robot) is introduced in place of the worker (staff man) who walk around with prism pole between land and water. In this method, the survey robot is amphibious walking robot. This system is not greatly affected by meteorological and oceanographic phenomena, and the robot can walk into the water a little deeply than the workers. Therefore, the proposed method can survey in the most important wave breaking area by the same method in land and water.

The proposed system mainly consists of survey robot which walks around autonomously with prism pole, automatic total station and host pc. The robot continuously moves on the survey path planed beforehand between land and water. The body position is measured by automatic total satation. The robot also follows and turn it's mirror to the total station. The relative feet positions are calculated using each joint angle. Therefore, we can obtain all topographic features on the survey path as cross-sectional diagrams using measured body and feet positions (Figure 2.).

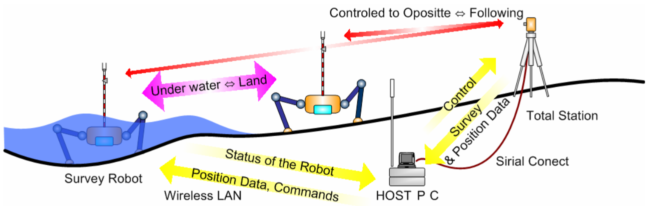


Figure 2. The image of proposed method for automated survey work.

3. DESIGN CONCEPT OF THE WORKING ROBOT

3.1 Configuration of the robot

The amphibious walking robot mainly consists of "1 body part with built-in battery, control and communications unit", "18 watertight type joint units" which are independent respectively to each other, "6 foot parts", and "structural leg parts" to tie to other parts. Joint units with same mechanism of all are connected using the structural leg parts.

Table 1. shows estimated principal dimensions and watertight of the amphibious walking robot.

Table 1. Specification of the robot

Items	Values
Leg length	500 [mm] (Lower thigh)
Body diameter	308 [mm]
Weight	80 [kgf] (In the air)
Watertight	0.3 [MPa] (Safety factor 1.5)

The watertight type joint unit applied joint unit #2 as inner unit which is developed [2]. Moreover, another gear reduction ratio version with 60 [W] motor was also developed up to 1/961.5375, and was applied to this robot. However, former all joint units were not submersible. Consequently, we newly designed and developed the watertight housing and applied to this usage.

The watertight type joint unit can use general devices such as DC brush motor, gear reducer and potentiometer as inner unit because the air of the atmospheric pressure has been sealed up by the unit. The motor torque is transmitted to the housing through the internal gear mounted in the housing, and we can extract the torque.

Figure 3. shows externals of the watertight type joint unit. Moreover, Figure 4. shows composition of inner unit in the water tight type joint unit.

We achieved the seal performance improvement by combination of single piece of seal and new sealing mechanism because there was a limit in the seal performance of the single piece. Especially, the seal made of rigid plastic cannot fit enough, and there is dread of remaining gap because the seal made of rigid plastic is hardly transformed.

In this case, the plastic seals were mounted double, and between two seals was filled with thicker fluid than the air or water. Namely, the low viscosity fluids such as the air and water were not separated directly mutually but the sea water and thick filler were separated with the outer seal, and the air and thick filler were separated with the inner seal. The filler was high viscosity grease and so on, and had a viscosity of the extent which did not leak through minute gaps. Accordingly, the new seal mechanism exhibit higher seal performance than single piece of seal secured when the volume of filled seal layer does not change [3][4].

3.2 Separation of watertight compartment of the body part and structural function

Whole of the robot was not made a waterproof. We held down the range of the watertight part as much as possible. Namely, only 1 body part and 18 joint units were made a waterproof independent respectively to each other, and they were mutually connected through the waterproof connectors. Moreover, legs of the robot were fixed on not to the body part but to independent frame.

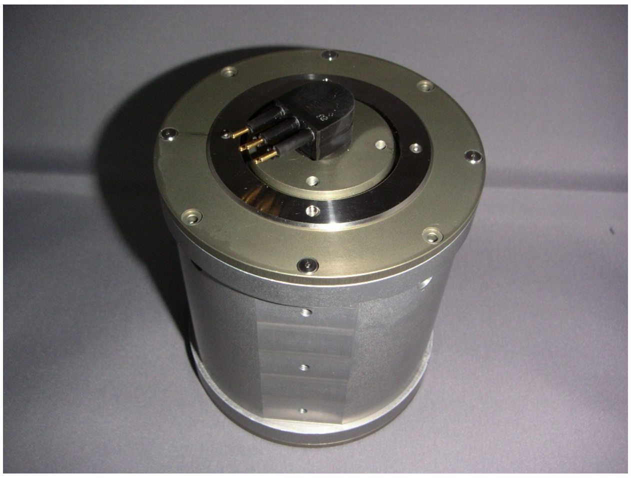


Figure 3. Externals of the watertight type joint unit.

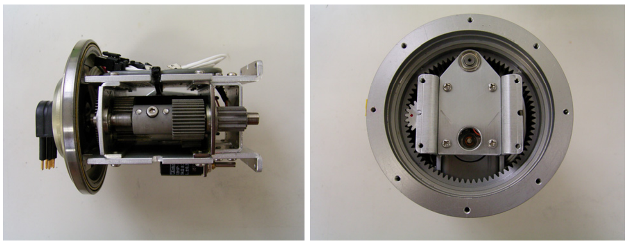


Figure 4. Composition of inner unit in the water tight type joint unit.

As a result, we might almost leave structural strength of the body part out of consideration. Namely, we could hold down the weight because we only had to consider only waterproof property. As a secondary effect, the legs and the body unit are able to be detached easily in case of the maintenance (Figure 5.).

3.3 Working range of the feet

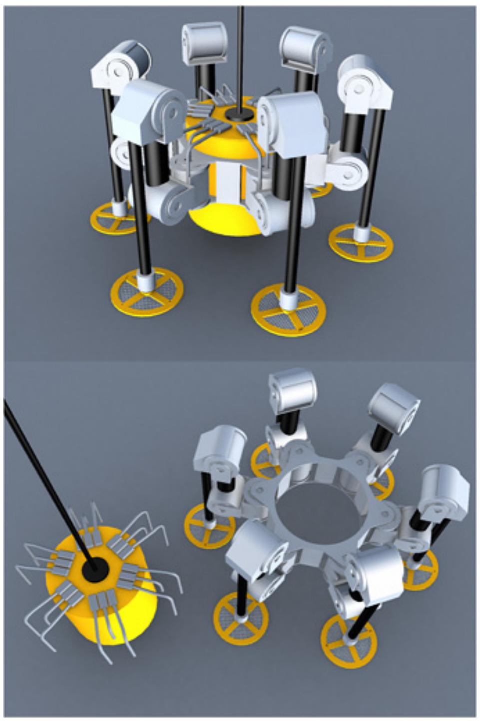
We have to decide the working range of the feet in consideration of inclination of the sand filled beach where our experiments are planed in order that the robot is made to work well. The global inclination was read off as about 1/25 - 1/30 from the findings of regular survey of the area in 2004. In the same way, the local maximum inclinations have not greatly exceeded 0.3 in the whole area according to the findings.

Consequently, we designed the working range of the feet of the robot as Figure 6. The cylindrical working volumes which are working range of the feet were constrained by range of movement of each joint angles and size of approximate working volumes. The volume sizes are used properly in total well.

4. OBTAINING GROUND CONDITION BY FIELD INVESTIGATION

4.1 Calculation of availability of travel based on exploration of ground

There is a determination methods for availability of travel on any ground using relation between ground capability and vehicle. "Trafficability" which is ground capability is measured as cone index *CI* by cone penetration resistance. "Mobility" which is road ability of vehicle is shown as mobility index *MI* and vehicle cone index *VCI* closely related a ground contact pressure and a configuration of contact part. Especially, comparison between *VCI* of the vehicle and *CI* of the actual ground is assumed to be an index of the developed vehicle performance because latter mobility is able to calculate by well-known method in response to *CI*.



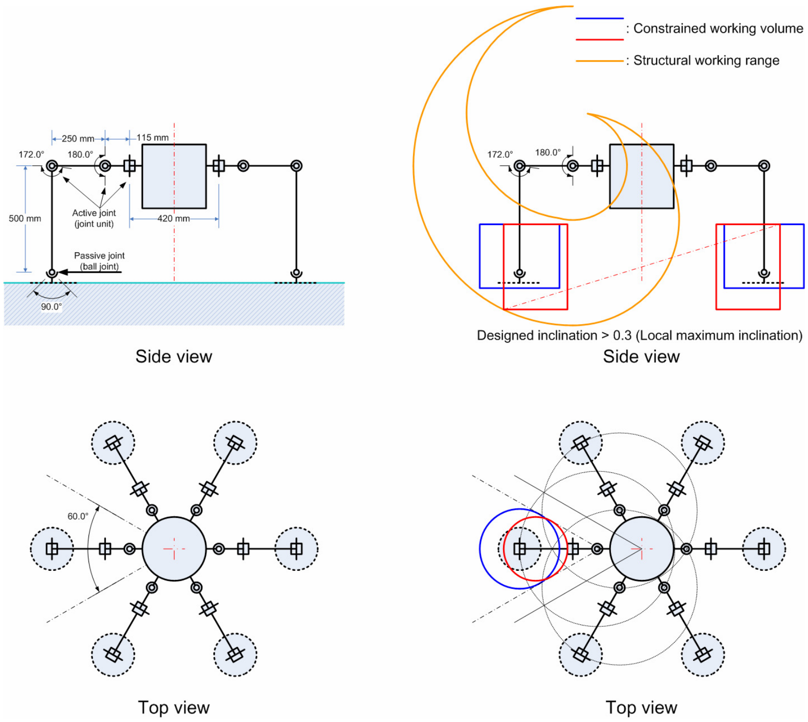


Figure 5. Image of removable body from leg unit.

a) Range of movement of joint angles b) Decision of working volumes

Figure 6. Main dimensions and working range of the feet.

Figure 7. In-site cone penetration test (Niigata West Coast).

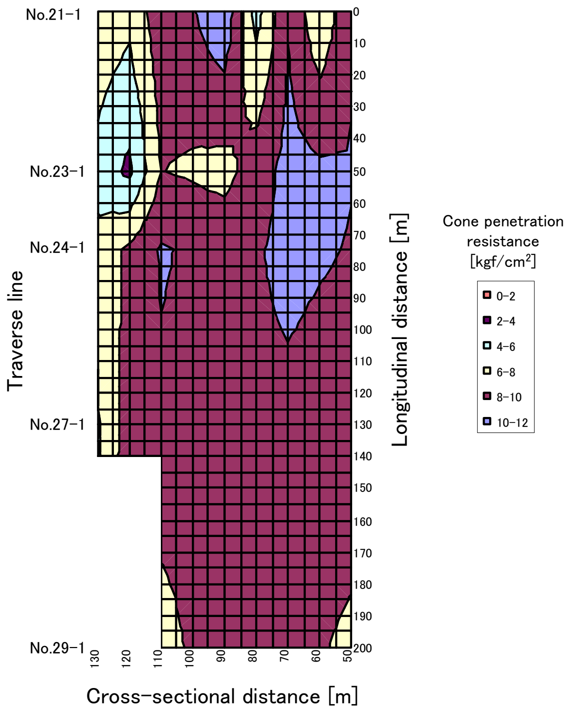


Figure 8. Distribution map of cone penetration resistances neighboring the first jetty of the Niigata West Coast (Depth: 10-20 [cm])

$$\text{Available; } CI \geqq VCI \text{ (Unit conversion)} \tag{1}$$

The determination method for availability of travel using trafficability is called mobility prediction method (WES method), and the method is usually used when wheel and crawler type vehicle are operated [5][6]. In this case, walking type is calculated based on the rule of crawler type although there has been no evincive case which is applying the method to walking machine because the feet come in contact with ground areally as well as crawler. We are out of consideration of the influence of kneading because contact of the foot is discrete.

4.2 Distribution of the surface cone penetration resistances in Niigata West Coast

We carried out in-site cone penetration test in the vicinity of the fist jetty of the Niigata West Coast, and obtained the cone index *CI* on the surface in June, 2004 (Figure 7.) [7]. *CI* in this discriminant is average *CI* by depth of 15.0 - 30.0 [cm] for ordinary vehicle, and is average *CI* by depth of 7.4 - 22.4 [cm] for light vehicle. The latter average *CI* indicates the trafficability on the robot weighting 80 [kgf] because it correspond to light vehicle. However, we used *CI* by depth of 10 and 20 [cm] because in-site cone penetration test is carried out every 10 [cm].

Minimum *CI*=3.56 [kgf/cm^2] and average *CI*=7.56 [kgf/cm^2] were obtained as results of the field investigation (Figure 8.). We use minimum *CI* which is most severe condition as the design target.

4.3 Calculation of vehicle cone index *VCI* and cone index of threshold limit *CI'*

VCI is closely related with contact pressure decided by the type, weight, and configuration of the travel device. The vehicle is excellent in the mobility when *VCI* is small. In this case, we calculate *VCI* using well-known empirical equation [5][6].

$$\begin{aligned} CI' &= CI = 3.56\,[\text{kgf/cm}^2] \\ VCI &= \frac{CI' + 0.0388}{0.071125} \approx 50.6\ \ [\text{kgf/cm}^2] \end{aligned} \tag{2}$$

4.4 Design of the foot part for ground condition.

Using empirical equation for crawler, minimum diameter of foot is shown by the following equation when minimum subgrade bearing capacity is 3.56 [kgf/cm2] and weight of the robot is 80 [kgf] and minimum number of contact legs is 3 [5][6].

$$\begin{aligned} VCI &= 125p = \frac{125G}{N\pi \cdot D_{\min}{}^2/4} = 50.6 \\ \therefore D_{\min} &= \sqrt{\frac{500G}{N\pi \cdot VCI}} \approx 9.16\,[\text{cm}] \\ p &: \textit{Ground contact pressure}\,[\text{kgf/cm}^2] \end{aligned} \tag{3}$$

Minimum necessary subgrade reaction is secured by a disk of 10 [cm] in diameter at center part of foot, and a ring of 20 [cm] in outer diameter and 16 [cm] in inner diameter at the marginal part corresponds to the margin. In ground contact area, the foot corresponds to a disk of 17 [cm] in diameter. So, *VCI*=14.7 and *CI'*=1.01 [kgf/cm^2] from Eq. (2), and the *CI'* is about 1/3 of *CI* of the beach (3.56 [kgf/cm^2]).

Moreover, we estimated foot settlement by equilibrium position of *CI*=1.01 [kgf/cm^2] and extrapolated line of *CI-S* using in-site cone test result. Consequently, the maximum settlement S_{max} was estimated to 1.16 [cm].

5. 1ST FIELD EXPERIMENT IN NIIGATA WEST COAST

We carried out 1st field experiment using developed automated survey system March, 2006. Table 2. shows primary components of the automated shoreline surveying system. Moreover, Figure 9. shows developed amphibious walking robot used to the experiment. And, Figure 10. shows developed software screens.

Table 2. Primary components of automated shoreline surveying system

Itemss	Specifications	Notes
Survey robot	Walking type (80 kgf)	Prism man
Total station	TOPCON GTS-820A (Automatic)	Positioning and leveling
Wireless LAN	JRC JRL-610AP	Robot/Host
PC	Note PC	Host
generator	HONDA EX6 (600 VA)	-

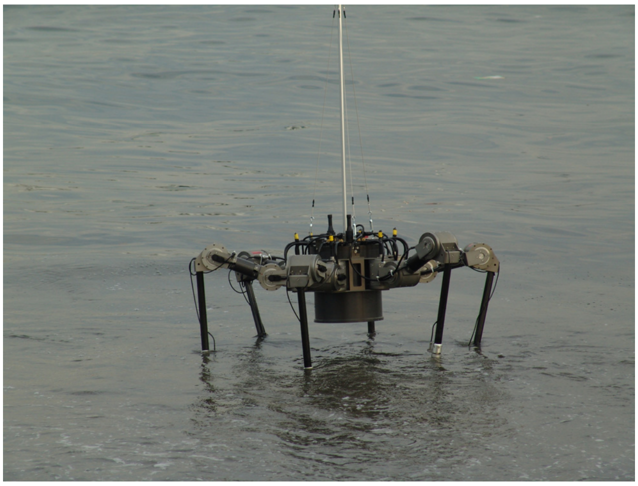


Figure 9. Amphibious walking robot which is prism man

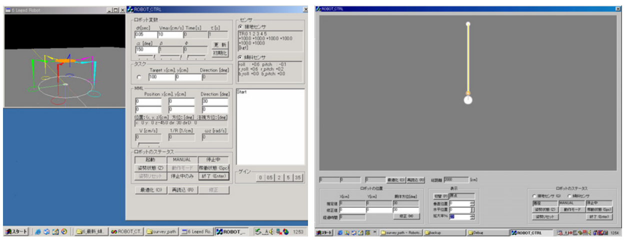


Figure 10. Software for robot control and navigation.

5.1 Survey experiment-1

At first, we surveyed some station points by humans on traverse line in order to compare the automated survey results with the man-powered survey results.

The start point was set at (+125 [m], +25 [m]) away from the triangulation station “Nishi-kaigan koen” (Code No. 5639-70-2402). The traverse lines were set in the direction of the crossing. And, the station points were set every 5 [m] on the line in accordance with general man-powered survey method in this beach.

In automated survey, the start point was set as well as the case of man-powered survey, and the robot carried out cross-sectional surveying. Figure 11. shows man-powered and automated survey results.

Error bars in the picture indicate ± 5.0 [cm] and all the differences between man-powered and automated survey results are up to 5.0 [cm]. In addition, foot settlements were very slightly.

Next Table and Eq.s show the average of difference, variance, and standard deviation.

Table 4. The differences between man-powered and automated survey

Point No.	Level (Automated)	Level (Man-powered)	Defference e
1	1.09 [m]	1.118 [m]	-28 [mm]
2	0.86 [m]	0.893 [m]	-33 [mm]
3	0.46 [m]	0.480 [m]	-20[mm]

$$\bar{e} = \frac{1}{n}\sum_{i=1}^{n} e_i = -27\ [mm] \tag{4}$$

$$\sigma_e^{\ 2} = \frac{1}{n}\sum_{i=1}^{n}\left(e_i - \bar{e}\right)^2 = 2.86667\text{E-05} \tag{5}$$

$$\sigma_e \approx 5.35\,[\text{mm}] \tag{6}$$

Average of difference is 27 [mm] while the data spread which is standard deviation is 5.35 [mm]. The topographic trend of obtaining by the robot is consistent with man-powered survey result. It follows that the major difference is bias component, and is estimated systematic error.

5.2 Survey experiment-2

In this case, the start point was set same as experiment-1 and the robot carried out cross-sectional surveying in the surf zone on the same traverse line as experiment-1. Figure 12. shows man-powered and automated survey results.

Error bars in the picture indicate ± 5.0 [cm] same as experiment-1, and all the differences between man-powered and automated survey results are up to 5.0 [cm]. In addition, foot settlements were very slightly and the topographic trend of obtaining by the robot is consistent with man-powered survey result same as experiment-1.

5.3 Making of contour plot (Post-processing of survey results)

We made a contour plot from experiment-1 result and the orthogonal oriented survey data. It was local because battery capacity and operating time of the robot was not enough at present. However, we could check the continuum work procedure from automated surveying to making of contour plot. And, we verified that the system could recreate the topographic trend with only few data. So, it is predicted that this system can recreate complex terrain with more traverse line by same work procedure.

Figure 13. shows contour plot made from survey data of automated survey system.

5.4 Consideration of the test result

In case of ordinary man-powered surveying, the accuracy of surveying with leveling in the air is millimeter order. However, it is difficult to bring its accuracy into full play because measurement object is transmutative sand beach and the work condition is more severe in surf zone. Moreover, in deeper area, the accuracy of sounding by vessel is about 10 [cm].

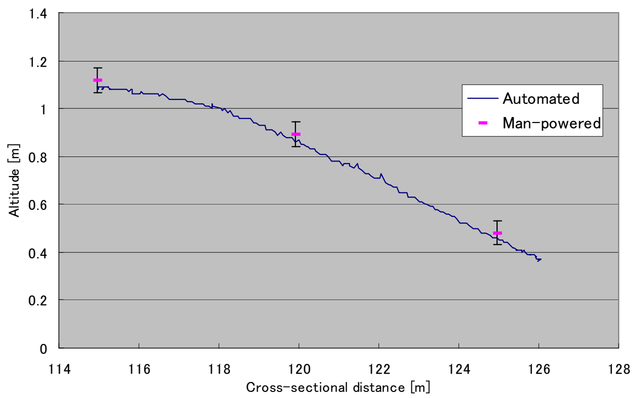


Figure 11. Comparison of automated with man-powered cross-section view of the beach.

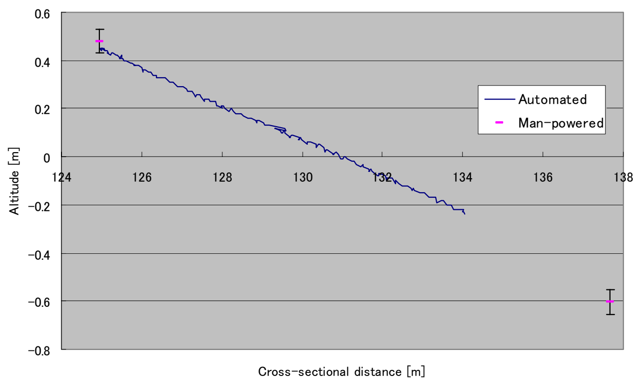


Figure 12. Comparison of automated with man-powered cross-section view of the beach (Surf zone).

The error factors of leveling are probabilistic "accidental (nonsystematic) error" and "systematic error" with some trend which is caused by settlement of sand and so on. Considering the purpose of shoreline survey is determination of sand volume variation, the vertical accuracy is reasonable because systematic error is reduced by periodical survey results comparison.

On the other hand, automatic total station has about 20 [mm] vertical accuracy according to the base-line length. It is predicted that the developed system has about 50 [mm] vertical accuracy because a number of vertical accuracy of automatic total station plus the difference between man-powered survey and automated survey results is less than 5.0 [cm]. And, it is predicted that the error is relieved by periodical survey results comparison because the principal component of error is estimated systematic error as shown in the section 5.1.

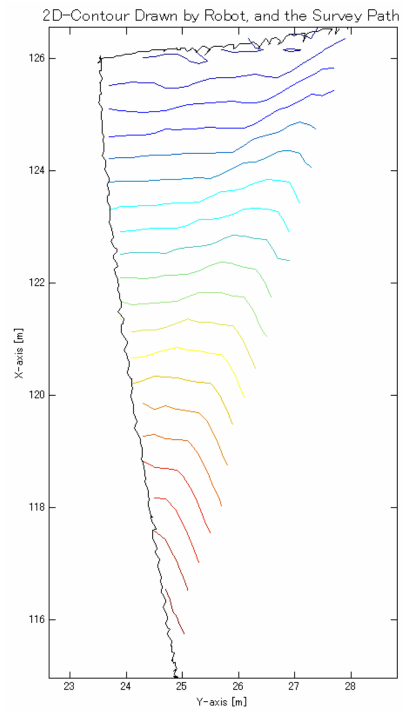


Figure 13. Contour plot made by automated survey.

6. CONCLUSION

This paper presented the design concepts and the features of the prototype robot applied moduled watertight structures for automated shoreline surveying system. Moreover, it reported the 1st field experimental result in the Niigata West Coast, and showed primal validity of the proposed method and important issue.

The issue is extension of operating time of the robot. It is predicted that the issue is solved by increase of the battery capacity and improvement of the system reliability. And, we will evaluate the proposed method additionally through repetition of field experiments with various improvements.

REFERENCES

[1] T. Tanaka, H. Sakai, and J. Akizono, "Fundamental Experiments for Automatization of Topographic Survey Work," *Proc. of ROBOMEC'03*, May 2003, pp.2A1-2F-24, in Japanese.

[2] M. Utsumi, H. Sakai, and J. Akizono, "Development of joint units and a serial communication method for reconfigurable and extensible robot system, "*Proc. of ROBOMEC'04*, June 2004, 1P1-L1-7, in Japanese.

[3] T. Tanaka, H. Sakai, J. Akizono, "Development of a Prototype Automatic Survey Robot in Shore Line, "*Proc. of ROBOMEC'04*, 2004, pp.2A1-L2-23, in Japanese.

[4] T. Tanaka, H. Sakai and J. Akizono: "Design Concept of a Prototype Amphibious Walking Robot for Automated Shore Line Survey Work," *Proc. of Oceans-Techno Ocean'04*, p.T-D-2-4, 2004.

[5] S. J. Knight, A. A. Rula: "Measurement and Estimation of the trafficability of fine grained soils," 1st Int. Conf. of ISTVS., Preliminary Copy, No. 24, 1961.

[6] S. J. Knight, D. R. Freitag: "Measurement of soil trafficability characteristics," Trans. ASAE., 5(2), 1962.

[7] T. Tanaka, T. Shiraishi: "Development of Amphibious Walking Robot Based on Moduled Watertight Structures", *Proc. of the 23rd Annual Conference of the Robotics Society of Japan*, 3I25, 2005, in Japanese.