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A Review of Mobile Robot Navigation System for Volcano Monitoring Application

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Abstract

Volcano is a geological environment including magma, eruption, volcanic edifice and its basements. For continuous monitoring after eruption, a mobile robot could be proposed as an alternative to prevent hazardous effect to volcanologist who perform up close monitoring. In this paper, the robots were divided into 3 types according to their different structures: legged, track-legged and wheeled mobile robots. Meanwhile, the navigation system were implemented in 4 steps suitable for volcano condition: environment mapping, trajectory design, motion control and obstacle avoidance. These navigation system also tested in different locations: indoor, outdoor and real volcano with different testing method for these robots. The testing result was discussed in robot kinematics parameter such as trajectory, velocity, slope angle, rollover and sideslip angels.

Keywords: mobile-robot, volcano, monitoring-system, navigation, control.

INTRODUCTION

Volcano is a highly complex geological dynamic environtment (not only an igneous system from the deepest root up to the surface), where all kinds of geologic process act on the rising magma, the eruptions, the volcanic edifice and its basement [1], [2]. There are more than 500 active volcanoes of about 1000 of volcanoes all over the world which fit with that definition [3]. It is needed a volcano monitoring sytem at each one of these volcanoes (at least for eaethquake, release of magnetic gases and surface deformation [4]) to reduce this natural disaster's risk [5]. Some unconventional system have been developed to overcome problems occure during the monitoring process [6], [7], [8], [9], [10], [11], [12]. However, during or after the eruption, the system may be broken and the hazard environment could be dangerous for volcanologist to fix the system while a continuous observation still be needed at the same time [13], [14].

Mobile robot technology could be the alternative solution in this situation (Fig. 1). Dante II, a legged robot for volcano exploration has been developed by NASA and Carnegie Melon University in 1999 [15]. Few years later, European Commission introduced their giant mobile robot called Robovolc for volcano observation [14]. Nagatani also reported his work about a novel multi-D.O.F. tracked vehicle, called ELF, which can conduct observation in a restricted volcanic area [16], [17]. Furthermore, there are some other robot for different exploration such as Artemis [18] and Merlin [19] for heterogenus surface and uneven terrain applications with suitable navigation system. Hence, the navigation and control system of the mobile robot should be able to detect and aboid hazard zone as well as generate path planning to specific target (s) [16], [17], [20], [21].

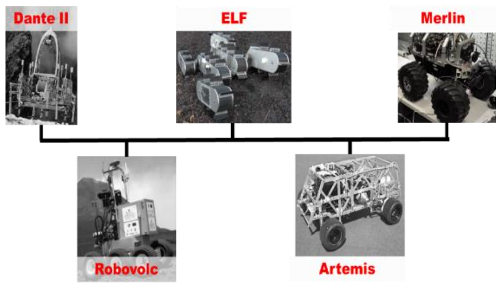

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Fig. 1. Mobile robot for volcano monitoring

This review will discuss about navigation system integrated with its control system for volcano monitoring application, the test, the test result and discussion and final remark for the system explained. The robot will be divided into 3 types according to their different structurus: legged, track-legged and wheeled mobile robots. Therefore, students who needs information about navigation system of mobile robots for volcano monitoring application could utilize the information.

NAVIGATION SYSTEM

Mobile robot navigation is the ability of a mobile robot to get from one place to another (destination) in an orderly manner required by the job, volcano monitoring for this case. This system can be divided into four steps: environment mapping, trajectory design, motion control and obstacle avoidance [22], [23]. To construct environment map, a mobile robot should be equipped with a proper vision system. Whereas for trajectory design, it is needed an inertial navigation to track the position and orientation of the object [24], to control the robot motion while avoiding obstacle(s) [25].

(1) Legged mobile robot.

Environtment mapping process is crucial for a legged mobile robot (such Dante II) to avoid obstacle or slip off precarious footholds by adapting to actual condition through continuously relating sensation to action this behavior-based architectures walking robot. Dante II – an eight-legged mobile robot - uses UI3D (a three-dimensional visualization and its surrounding terrain) and [15] VEVI (Virtual Environtment Vehicle Interface, a modular operator interface for robotic vehicles) to generate local elevation map and to utilize real-time, interactive, 3-D graphic and feedback from onboard sensors [15], [26] (Fig. 2).

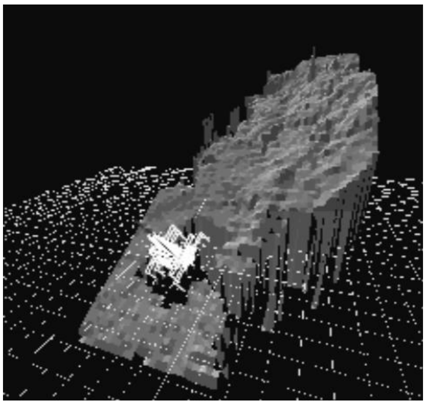

Fig. 2. Environment 3D mapping of Dante II [15]

Determining the most effective parameterization of the gait behaviors by collection of individual planners is suitable trajectory planning for Dante II [15], [27], [28], [29]. This gait behavior (in Dante II has 24 asynchronous process: eight contact-foot behaviors to stand, eight freefoot behaviors to step, one each of raise-legs, move-frame, turn-frame, lower-legs, and sit-still behaviors to walk, and roll, pitch, and clearance behaviors to posture) together with control process, allows the foot to move, halt or reflex to some environment condition (vertical or horizontal terrain) e.g if it loses contact with the ground [15], [30], [31].

The gait-control process run in onboard processor. Furthermore, this real-time control motion (in one or more processor(s)) collects sensor information, write the state into shared memory, drive the eg PD servo loops, service for translation, turn and tether actuators [15], [30], [31].

This motion control also responsible for obstacle-crossing capability by the free-foot behavior [15], [30], [31]. Shortly after the robot detect obstacle, the legs raise up in coordination with a momentary pause in body motion [15], [32], [33], [34].

(2) Track-legged mobile robot.

Generlly, there is no environment mapping for a track-legged mobile robot such ELF (specially made for weak and uneven terrain of volcano). It is because its robust locomotion performance to explore different terrain and texture as well as “climbing” the obstacles [16], [17], [35]. However, trajectory planning is designed as simple as possible, hence the robot should only move in a straight desired path to the destination [16], [17], [35].

To reduce downhill slide slip in volcano area, the robot poster should be controlled verticaly to gravity [16], [36], [37]. Moreover, an orientation controller is added for the transversal motion by creating a gap in the locomotion velocities of both main tracks [16], [36], [37]. This main tracks and 4-subtracks coordinate for entire robot motion commanded by a control unit via wireless LAN [16], [36], [37] (Fig. 3).

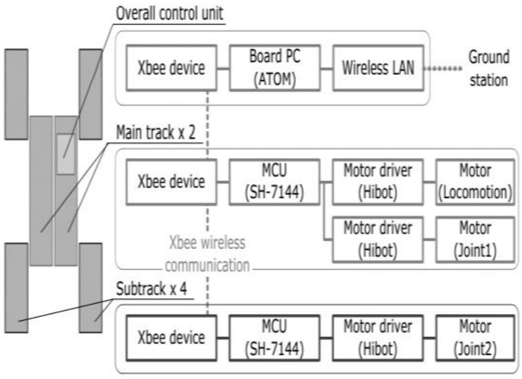

Fig. 3. Configuration of ELF's controller (adapted from [16])

(3) Wheeled mobile robot.

The navigation system for wheeled mobile robot usually implemented into four layers: long range planning, short range planning, instant path planning and control motion as we can find in Robovolc, Artemis and Merlin [14], [18], [19], [38]. Long range planning is the layer for generating an environment map base on waypoints built by sensor input from fixed cameras (5 cameras including IR camera in Robovolc), ultrasonic sensors etc. [14], [38]. Short range [14], [18], [19], [39], [40] and instant path plannings [14], [18], [19], [41] are responsible for trajectory planning process to manage the navigation between the waypoints and decide the direction of the robot. Furthermore, the motion control layer transforms this plans into control commands for motion control boards [14], [18], [19], [42], [43], [44], [45].

In Robovolc, a localization system to determine the exact location of the robot has been performed in two ways: Self Kalibrating Extended Kalman Filter (EKFSC) and orientation estimator [14]. Moreover, the obstacle avoidance is teleoperated by volcanologist through the vision of its cameras [14].

On the other side, ARTEMIS a 4 wheeled mobile robot as Merlin, concludes the four steps of navigation system in one algorithm.

A high-level control layer generated some waypoints as the mobile robot optimal trajectory [46]. On the other side, the low- level layer navigated robot through this trajectory via potential field [46] – an elegant hybrid method both for reactive and deliberative behavior of its environment [19] which can deal with complex obstacles [19] as well as controlled to the desired point. To control optimal trajectory, it was performed a look-a-head model for navigating the mobile robot without failures [46] through checking the collision with its environment [19].

The algorithm for this method is as followed:

1. The value of the net potential field at the robot's current position in trajectory space (TS) is calculated from Eq. (1). Position in TS is a curvature-velocity (κ,v) pair [46].

$$PF(\nu,\kappa) = PF_r(\nu,\kappa) + PF_s(\nu,\kappa) + PF_g(\kappa) + PF_v(\nu) + \sum_{i=1}^{n} PF_0^i(\nu,\kappa) \quad (1)$$

Where, $PF_r(\nu,\kappa)$ is potential field for rollover constraint, $PF_s(\nu,\kappa)$ is potential field for side slip constraint, $PF_g(\kappa)$ is potential field for corresponding to the current desired waypoint location, $PF_v(\nu)$ is potential field for desired velocity, and $\sum_{i=1}^{n} PF_0^i(\nu,\kappa)$ is potential field for hazard locations (including other obstacles) [46].

2. The gradient of the net potential field is computed, and a desired maneuver (i.e. a (v,κ) pair) is chosen in the direction of maximum descent [46].

3. The predicted trajectory of the robot is computed via forward simulation of a rigid body model (Fig. 4) subject to the desired maneuver over time dt, where F is the sum of all the horizontal tire forces, R the sum of all normal tire forces, and the weight is mg [46].

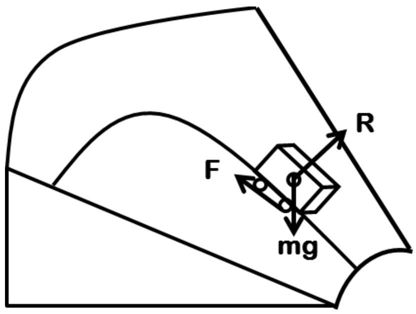

Fig. 4 Rigid body model for mobile robot simulation (adapted from [46])

4. Steps 1-3 are repeated while t (virtual time in a forward simulation loop) is no more than T [46].

5. A maximum safe velocity profile is computed over the predicted path. Maximum safe velocity profile was defined from the cost function $J = \int_{s_1}^{s_2} \frac{ds}{\dot{s}_m}$,

where J is cost function (time), ds path arc length, $\dot{s}_m$ maximum safe speed [46].

6. The predicted robot velocity profile is compared to the maximum safe velocity profile [46]. Robot velocity profile $\dot{s}$ is the solution from Eq (2), (3), and (4)

$$f_t = mgk_t + m\ddot{s} \tag{2}$$

$$f_q = mgk_q + m\kappa n_q \dot{s}^2 \tag{3}$$

$$R = mgk_r + m\kappa n_r \dot{s}^2 \tag{4}$$

where f_t and f_q are components of the friction force tangent and normal to the path, κ the path curvature, k is a unit vector pointing opposite of the gravity force, n is a unit vector pointing in the direction of the path center of curvature, and the subscripts denote projections along the path coordinate frame, t, q, r.

If the predicted velocity profile exceeds the maximum safe velocity profile at any point, the robot's desired velocity is reduced to the maximum safe velocity along the trajectory.

The navigation system for these mobile robot could be conclude in Table 1.

Table 1. Camparison of mobile robot navigation system

	-Mobile Robot		
	Legged-	**Track-legged-**	**Wheeled-**
Environment Mapping	UI3D-VEVI	-	Long range planning, waypoints-potential field
Trajectory Design	Gait behaviours	Move in straight path	Short range planning, look-a-head model
Motion Control	Gait-control	Robot poster controlled vertically, orientation controller for transversal motion	Motion control layer
Obstacle avoidance	Free-foot behaviour	-	Camera vision, look-a-head model

TESTING METHOD

The navigation system of a mobile robot should be tested to meet the design requirement before it is used frequently and repeteadly [47]. The different testing method for 3 different kind of robots will be explain here.

(1) Legged mobile robot.

Flat-floor walking was the first test for a legged mobile robot, Dante II including body translation, turning [48], maximum body lifts [49], [50], and coordinated winch operation [15], [51]. The next test is walk on a 30°, 7-m-long ramp while maintaining a gravity-balancing tension on the tether cable including walking, turning, and obstacle-crossing capabilities [15], [52], [53].

For outdor testing, the robot was tested on a hillside [15], [54], [55], [56]. The path included a 10-m steep slope (50°) followed by a 5-m flat area, which transitioned into a 30-m variable-slope region (20–50°) to the top. The path also included some minor (about 10◦) cross-slopes [15], [57], [58], [59]. The terrain was hard soil covered with light vegetation [15]. Furthermore, the mixed-terrain testing was held on a 5-m flat section of the path covered with large boulders (0.5–1-m tall) in an effort to emulate the worst-case conditions expected [15], [60].

Dante II was also tested on full-scale volcanolike terrain [15], [61], [62]. Some test were conducted along a 170-m path. The upper portion of the path is level for 40 m, and then slopes into a smooth escarpment of 30–40° for 70 m and 40–50° for 5 m, and then follows a moderate but trenched uphill grade for 60 m [15].

The final destination for robot teting was a real volcano. Dante II was tested on Mout Spurr, Alaska which consisted of three segments: descent to the crater floor, floor exploration, and ascent [15].

(2) Track-legged mobile robot.

One of the greatest challenges is downhill sideslip often found in volcano. To reduce this slip, ELF was controlled to remain vertical with respect to gravity by a mechanical model based on terramechanics theory for the robot which has the capability of swinging its subtracks while maintaining its attitude [16], [63], [64], [65], [66].

An indoor testing in a simulated volcanic field [67] with 3 m and 1 m of length and width respectively with pumice stones whose bulk density was less than that found in actual volcanic fields, has been performed to confirm the effectiveness of the controller in navigation system [16]. The test was held in 30^o of 5^o interval of slope angle where for each angle two configurations of the robot-normal contact and horizontal contact were examined, and three trials were conducted using the same configuration at 8 cm/s of velocity [16]. The slip angle (β) on the slope [68], [69] was evaluated using Eq. 5 [16].

$$\beta = \tan^{-1}\frac{v_y}{v_x} \qquad (5)$$

where v_x denotes the locomotion velocity of the robot and v_y denotes the sideslip velocity.

The test also conducted on a real volano of Mount Kushigata where the slope (about 30^o) was covered by scoria (weak soil) with 12 cm/s of velocity and 10 m navigation distance in two configurations as well [16]. The robot's trajectory was recorded by the surveying equipment [16].

(3) Wheeled mobile robot.

The robot parameter for odometry [70], [71], [72], [73], [74] of Robovolc was as follow: wheels radius: R_1 = 0.21m, R_2 = 0.21m, wheelbase: L = 0.82m, while for EKF algorithm [75], [76], [77], [78], [79] was used DGPS [14], [80]. Meanwhile, ARTEMIS 0.89 x 0.61 x 0.38 m of dimension, which has 700 MHz Pentium III PC -104 onboard computer, Crossbow AHRS-400 INS, a tachometer to measure wheel angular velocity, 20 cm resolution DGPS, and Futaba steering and throttle control servos, was tested on a flat, bumpy terrain covered with grass [46]. To study an obstacle avoidance [81], [82], an obstacle of 1 m radius was set at (x,y) = (15.0, 0.0) and a waypoint was set at (x,y) = (30.0, 0.0). The desired velocity was set at 4.0 m/s. Note that for a vehicle of this size, rollover [63], [83] can easily occur at 4.0 m/s [46].

The three different testing method are concluded in Table 2.

Table 2. Testing method for navigation system of mobile robots

	-Mobile Robot		
	Legged-	**Track-legged-**	**Wheeled**
Indoor	Flat-floor walking (body translation, turning, maximum body lifts, and coordinated winch operation), walking on a ramp (walking, turning, and obstacle-crossing capabilities)	In a simulated volcanic field with pumice stones in a hill surface (mechanical model based on terramechanics theory): slip angle	on a flat, bumpy terrain covered with grass: waypoints and obstacle avoidance.
Outdoor	On a hillside with different slopes on hard soil covered with light vegetarian, on a volcanolike terrain	-	-
Real Volcano	At Mount Spurr: the crater floor, floor exploration, and ascent	At Mount Kushigata: slopes covered by scoria: robot trajectory	At Mount Etnaa: odometry and DGPS

RESULTS AND DISCUSSION

Some parameters usually discuss in mobile robot navigation system are: trajectory [23], [84], [85], [86], velocity and angles [87] (rollover, sideslip, slope). In this section the testing result will be discuss regarding these parameters.

(1) Legged mobile robot.

Flat-floor walking testing efficiently conducted without major problem as well as on a ramp testing and a hillside beside a building [15]. The robot was set to far away from the user as well as communication bandwidth limitation in extremely hot weather and rain as actual mission later [15], [88]. The robot could provide terrain information through its cameras and scanning-laser range finder [15]. In a hillside location, the robot run for 182 steps over 111 m in 219 min for an average speed of 0.51 m/min, where the roll and pitch were maintained to within ±2^o [15]. The free-foot reflex was effectively implemented where the feet could skim the ground, providing protection against tipping, and raise up if they bumped [15]. The mission was conducted in over 30 hour period where the vision system could work properly [15]. However, the behavior required only 179 min (2:59) with the gait controller averaged 0.51 m/min, and in some areas averaged 0.67 m/min [15].

Mount Spurr is the final desination for Dante II where has a crater that could no be entered by volcanologist [89] which has cross slope up to 30^o with 23.3 min (0.42 m/min) of autonomous walking for 9.8 m [15]. After the robot facing a dead end, Dante II turned around and made two autonomous descents down in 35.2 min (0.24 m/min) for 8.3 m and 12.3 min (0.49 m/min) for 6 m [15]. The laser-built 3-D elevation maps have been successfully generated and used during the exploration [15]. However, the laser scanner had become obscured by airborne volcanic ash [15]. Therefore, the vision only obtained by the cameras [15]. The communication and power have lost during the escent exploration because of a moisture-related short circuit in the power cabling at the rim [15]. Moreover, it also fell (on the side) due to a combination of factors including steep slope and cross-slope conditions, soft unstable slope material, a destabilizing tether-exit angle, and a control algorithm that had never been tested in such perilous stability conditions [15].

(2) Track-legged mobile robot.

From the test result, it could be explained that the contact plane should be set horizontally when traversing a weak slope, which caused the tracks should be configure to adapt to the target slope angle for up to 25^o [16]. Therefore, an orientation control has been applied by creating a gap in locomotion velocities v_l and v_r by Eq. 6 and 7 [16].

$$v_l = v + c\varphi \tag{6}$$

$$v_r = v - c\varphi \tag{7}$$

where v is velocity, c is coefficient vaue and φ is yaw angle obtained by the IMU [16], [70], [90], [91].

Moreover, according to its 3D-trajectory it is shown that the robot generated a higher degree of sideslip than it did with the horizontal contact configuration, with 2.7 m deviation from desired path at point 7 m, then be reduced in horizontal configuration by 58% which could make the robot survive in a weak slope where the controller contributes to the suppression of its trajectory [16]. However, the slideslip stoped when the orientation of robot became -15^o. It could change in a downhill at any time where slidesip occure contonously in angle of 30^o of normal contact configuration where the robot could not change the orientation because it dug into the ground [16]. The slip angle in the horizontal contact configuration was less than half of the angle in the normal configuration where a small degree of slideslip occurred in 10^o slope angle [16].

(3) Wheeled mobile robot.

The odometry parameters could be estimated when the robot (Robovolc) moving along the trajectory: R_1 (t=90) = 0.209 m, R_2 (t=90) = 0.208 m of wheel radiuses and L(t=90) = 0.816 m of wheel base in a real volcano of Mount Etna [14], [92]. EKFSC method showed satisfy result which reconstruct the trajectory which very close to the real one, and better than others method (EKFClasic and EKF calibrated via UMBmark) with average speed of 0.81 m/s [14].

Furthermore, a car-like mobile robot such as Merlin and ARTEMIS have shown significant results for the navigation system from the testing inside laboratory. An obstacle has been successfully avoided and the waypoints have also been reached. GPS offset result in an nitial heading error. The velocity was controlled to decreas at a large curvature to avoid the obstacle (i.e. around x = 15.0 m) near 4 m/s in save region (i.e. after x = 25.0 m) without rollover and slideslip. Moreover, the testing with 3 waypoints has also succecessful result where the robot navigated to and reached the waypoints where velocity was controlled near 4 m/s in save region and also decrease at large curvature.

These results are concluded in Table 3.

Table 3. Result testing of mobile robots

	-Mobile Robot		
	Legged-	**Track-legged-**	**Wheeled**
Trajectory	Following the path of 3D elevation map	Generated higher degree of sideslip	Following the waypoints generated by high level planner, odometry
Velocity	Varied (under 0.6 m/min) according to the slope	8 cm/s	0.81 m/s (average speed for Robovolc), controlled near 4 m/s or uder in a large curvature (ARTEMIS)
Slope	Up to 30^o	Up to 30^o	Up to 30^o
Rollover/Fell	Fell on the side	-	-
Sideslip	-	Occure continuously at 30^o of normal contact configuration, stoped when the orientation of robot became -15^o, in horizontal contact configuration: 10^o	-

CONCLUSION

To prevent the hazard for volcanologist during volcano monitoring, there have been developed mobile robots for monitoring of volcanoes. Volcano is a challenging environment to be explored. Therefore, the robot should be equipped with a proper navigation system. Thede robot were divided into 3 types: legged, track-legged and wheeled mobile robots which have 4 steps of navigation system: environment mapping, trajectory design, motion control and obstacle avoidance. Legged mobile robot concerned in its gait behavior, while tracked-mobile robot on its motion control with no step of obstacle avoidance, and wheel mobile robot more concerned about rollover and slide lip angles. The navigations sytems have been tested in indoor, aoutdoor and real volcano and discussed in some parameters: trajectory, velocity and angles. These robots have been autonomously move along trajectory generated by high level planner through 3D map generation, slideslips data, waypoints and odometry parameters while moving in controlled velocity under 4 m/s (the fastest) on a slope up to 30^o. There was no rollover experienced by the robots, except for the legged robot which fell on its side during walking on the slope. Sideslips only occured continuously in track-legged mobile robot at 30^o of normal contact configuration and 10^o in horizontal contact configuration.

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