Neural, Parallel & Scientific Computations 15 (2007) 319-334

COLLISION SIGNAL PROCESSING AND RESPONSE IN AN AUTONOMOUS MOBILE ROBOT

FUJUN HE, ZHIJIANG DU, LINING SUN, AND RUI LIN

Robotics Institute, Harbin Institute of Technology, Harbin 150001, China.

ABSTRACT. An autonomous mobile robot is easy to collide with moving object in dynamic environment, it should have the ability to identify a collision and make reasonable response to it. The paper introduces a method to perceive collision by detecting the vibration of robot with a two-dimensional accelerometer on a differential drive wheeled mobile robot. The features of acceleration signal caused by pure collision is analyzed, and the rules to determine impact direction are set up based on the resultant impact force. Since the accelerometer is sensitive to gravity and may confuse the impact acceleration with other running accelerations, the accelerometer information is processed to identify whether a collision occurs and a detecting window based on median filter is designed to extract pure collision information. A responding strategy is established to avoid further impact as soon as possible and manage to find the knocking object. The experiments show the robot can perceive impacts on several typical situations and make response in acceptable degree.

Key Words Mobile robot, Bump detection, Signal processing, Accelerometer.

1. INTRODUCTION

The wheeled mobile robots are extensively used as service robot, entertainment robot, transport robot and so on for their flexible actions. It will collide on some obstacles or knock by some quickly moving objects inevitably although the robot may equipped with sensors such as camera, ultrasonic sensor or laser ranger. These sensors all have their dead zone, and the responding time, distinguish ability and sensing range may also cause the robot ignore some quickly approaching objects. Once be knocked the robot should be conscious of it and make a response to it. In the case of an entertainment robot, a boy may play a ball with it. He throws the ball to the robot from the back and wishes the robot turn back to see who assault it. The robot is even expected to find out and catch the ball. So the robot should have the ability not only to feel a knock but also to be aware of the collision direction and the impact force.

How can a robot perceive a knock on it? We may get some hints from ourselves, if something hits on us, we can know the contact position by tactile sensors in our skin, the strength by press degree and the hitting direction by the falling trend. But

Received February 15, 2007

it is impossible for a robot to install so many types of sensors all over its body, a reasonable solution may be to install a limited kinds and numbers of sensors to realize most of the function. A choice is to utilize accelerometer to sense collision [1]. In fact many accelerometers have been used in robots to help localization or to get velocity information [2, 3, 4]. Accelerometers are also used in some devices to detect impact and vibration, but only to feel when the collision happens. The accelerometer is also applied on the cleaning floor robot to avoid serious hit on obstacles [5, 6]. Some hand-held surgical devices also use accelerometer to feel vibration caused by interference with body [7, 8]. But these applications of accelerometer are either on low mass devices that need small force to trigger a vibration or in the case that a large force is needed to inspire accelerometers [9]. Most of these applications of accelerometer are only to perceive a collision. Yet the mobile robot will run on more challenging terrain such as a slope, fluctuant land or rough road, which will bring vibration signals to accelerometer, blending with collision signal. At the same time, the acceleration of a running robot will continue to vary, which will also confuse with the acceleration caused by a collision. The robot not only needs to identify a collision, separate the impacting signals from other vibration information but also to evaluate the direction of a collision and make a reasonable response.

There are several useful signal analysis tools such as Fast Fourier Transform and Wavelet method, but they are not suitable for the acceleration signals compounded with collision information. To realize the approximate real time signal processing, the single separation and interpretation are carried out in time domain. The first order difference method and median filtering method are used. The separated collision signals are further analyzed based on character of resultant acceleration to determine the impact direction and then the robot should make a reasonable response to it.

In this paper a three-wheeled differential drive mobile robot is used to carry out the study, which is installed a 2-D (two dimensional) accelerometer for collision detection [10]. The purpose of the research is to check the possibility of collision detection with only one 2-D accelerometer, to find out the characters of vibration signals caused by impact, and manage to find a method that can effectively extract the bump information from the vibration signals. The paper analyzes the response specialty of the accelerometer when the robot is knocked by a ball from different direction. A rule is proposed to determine the right impacting direction from the vibration signals, and a reacting policy to the bump is also presented. Experiments are carried out to check the method, which give some significant results.

The reminder of this paper is organized as follows: In section II, we introduce the character of the robot and the consideration of how to equip the 2-D accelerometer. The static collision signals are analyzed and a method to extract the impact direction angle is presented in section III, the section IV discusses how to identify collision signal and separate it from the confused acceleration signals, in section V the reaction policy of the robot to a collision is proposed accordingly. In section VI, the experiments are carried out to verify the proposed method and a discussion about result is addressed. Finally, the conclusion of this paper and some future works are discussed in section VII.

2. ROBOT AND INSTALLATION OF ACCELEROMETER

A three-wheeled differential drive mobile robot is designed to act as a research platform. Fig. 1 shows the construction of the robot. Since the accelerometer readings may be directly affected by the arrangement of wheels, the size of the robot and so on, the related parameters will be introduced as follows. The two front wheels are the driving wheel, which are pneumatic rubber tires with the diameter of 190 millimeter. A caster wheel with the diameter of 75 millimeter supports on the back to balance the robot, which is made of polytetrafluoroethylene. The distance between two wheels is 377 millimeter, and the gravity center is 50 millimeter back to the axis of front wheels. The weight of the robot is 19.5 kilogram. The Cartesian coordinate system is adopted with the right x direction complies with the front side of robot as show in Fig.1. The robot adopts double layer control structure, in which the lower computer of DSP and CPLD control the basic motion of wheels and the upper computer of a Pentium-M 1.5 gigahertz single board computer performs sensor's signal collection, processing and task planning. Since the platform is used for service robot, it is also equipped with gas sensors, inclinometer and gyroscope other than accelerometer. All these sensors are managed by a single board, which sends sensor information through RS232 interface to the upper computer. Although collision occurs instantly, the robot with pneumatic tire will vibrate as an elastic body, from test such a sample rate of $5ms$ can obtain complete vibration information.

Preliminarily only a 2-D accelerometer is applied, which is installed on the middle point between two front wheels to avoid the additional effect of centrifugal force when bump force does not pass through the gyration center. The coordinate system accords

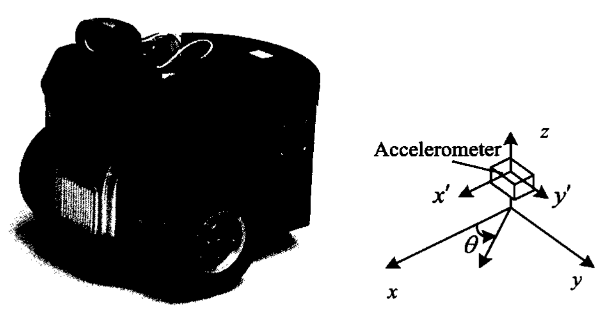


FIGURE 1. Robot, accelerometer and their coordinate system

with that of robot as shown in Fig.1. The angle in the coordinate system is defined as right from $0°$ to $180°$ when measures counter clockwise from x-axis, and $0°$ to $-180°$ when measures clockwise.

3. DETECTION OF STATIC COLLISION

3.1. **Features of collision signal.** When the robot stops on horizontal floor, the accelerometer can only collect the vibration signals caused by collision, which is called static collision. The paper firstly begins with the pure impact collision signals to find out its features and manage to determine the direction of impact. The robot may be knocked from any direction, but according to the external shape of robot body there are several most likely impact modes: from front to back or from back to front, vertically to the lateral wall of robot and on the four corners with the impact angle of near $\pm 45°$ and $\pm 135°$, another mode is to impact directly on the end plane of tires. Different mode of collision will initiate different accelerometer signal. We firstly take the impact mode of from front to back to illustrate the feature of the induced vibration acceleration signal. Other modes of impact will be discussed in the experiment.

A soft volleyball is rolled quickly to knock the front wall of robot along converse x-axis from a distance of 1 meter. Fig.2(a) shows the acceleration curves of x and y directions respectively for 4 knocks. There is a longer period between two knocks to let the robot calm down in the experiment, but part of the static signals between two knocks have been removed to show more vibration slips in the figure. There is great difference among these vibration signals in amplitude for the impacting force is different for every impact to reveal as much signal features. Although the impact is made along the x-axis as much as possible, the acceleration along y-axis is relatively high, which will lead to an error to impact direction evaluation. One reason may be that the ball not rolled exactly along x-axis, a lateral friction on the robot will cause the vibration along y-axis. What is more, even the ball's rolling direction exactly parallel to x-axis but with the knock point deviating from the mid-point of front side, a torque to the gyration center will occur, which will easily cause an oscillation. Such an oscillation will be the source of lateral vibration, which is especially obvious for the three-wheeled structure. The acceleration signals will fluctuate for a period, how to determine the collision direction?

3.2. **Determination of resultant force.** In fact it is difficult to determine the impact direction only by acceleration values, yet the resultant force will reveal more information, so the resultant force should be computed. Since the angle defined in robot coordinate system is from $0°$ to $\pm 180°$, the resultant force angle may be determined by

$$\theta = \begin{cases} 90 & a_x \to 0, a_y > 0 \\ -90 & a_x \to 0, a_y < 0 \\ \pi + a\tan\left(a_y/a_x\right) & a_x < 0, a_y \geq 0 \\ -\pi + a\tan\left(a_y/a_x\right) & a_x < 0, a_y < 0 \\ a\tan\left(a_y/a_x\right) & a_x > 0. \end{cases} \tag{3.1}$$

Where θ is the angle relative to x-axis, and a_x and a_y are the accelerometer readings along x and y direction respectively. The resultant force of each pair of acceleration value can also be obtained by

$$F = m\sqrt{a_x^2 + a_y^2}. \tag{3.2}$$

According to (3.1), and on the base of a predetermined acceleration threshold, the fluctuation of resultant force and its direction are show in Fig.2(b) and Fig.2(c)

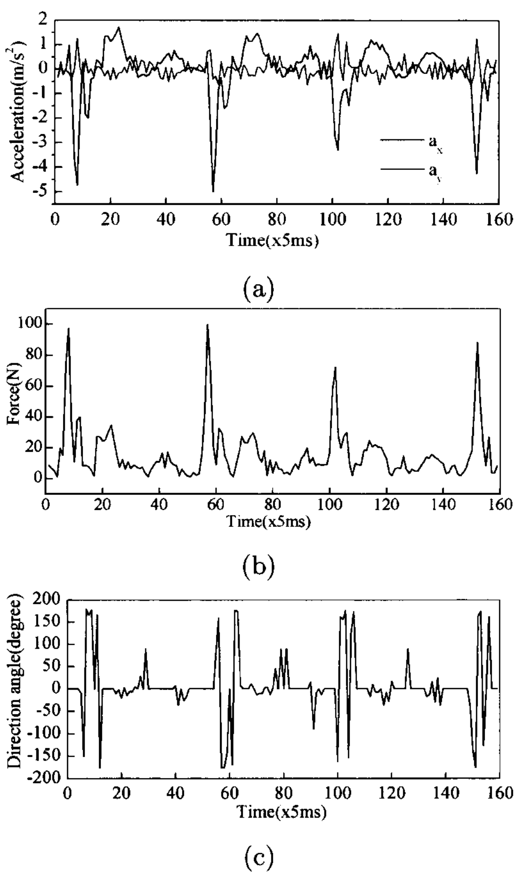


FIGURE 2. Acceleration signals, resultant force signal and the direction signal when knocked from the back of robot with a soft ball

respectively. The 4 largest vibration angles in Fig.2(c) are $-174°$, $177°$, $177°$ and $-175°$ corresponding to the 4 impacts. Although the angle of $-174°$ and $177°$ is greatly difference in value, but the direction they point to is nearly the same one ($180°$). From Fig.2(c) we can see that in most cases the largest angle occurs where the resultant force is the largest during one impact, but there are also exceptions, for example in the first bump, the angle corresponding to the largest force is $166°$. It is normal to see the largest angle is not corresponding to the place of the largest force. This implies that it is not rational to determine impact direction just by the largest angle or the angle of the largest force.

3.3. **Determination of bump direction.** Since the sensor is sensitive to the terrain, the accelerometer zero point will drift if the support surface of the robot is not horizontal, so the robot will determine a new sensor zero point every time it starts or after a specified period.

There are many artificial intelligence methods to classify the data from a collection such as the Rough Set theory, the Neural Network theory and the Support Vector Machine theory. They are useful especially to identify the data from a data collection without obvious classifying rules. A feed forward neural network can be trained to identify the impact direction according to the features extract from the resultant force spectrum and its direction spectrum. But in this paper we manage to find some simple rules to simplify the processing and to find the features of the signal for future analysis.

From the acceleration signals the robot's vibration may be classified as violent vibration or general vibration. The violent vibration here may has a longer vibration period than general one, but it does not mean the vibration force of violent vibration is much larger than that of general vibration, it is caused by a different knock mode such as the impact on wheel is easy to induce violent vibration. Such a classification is meaningful for the impact direction extraction since these two vibration modes have distinct ways to judge the impact direction. For the situation that the acceleration threshold of $0.5m/s^2$ is set, under a medium intensity impaction, the violent vibration have a longer vibration period, the largest vibration force happens on the middle of the vibration period and the first vibration force is smaller at least than two of the serial data. According to the two vibration modes it is suitable to judge the impact direction with the information of the first vibration force and the largest vibration force. The judging rules are concluded as follows.

Suppose the largest vibration force is F_m, and the force just before the largest one is F_f, then under general vibration mode:

IF $F_m > 1.5F_f$

IF the angle of the largest force has the same sign with that of its following two forces

Bump angle = −largest force angle;

ELSE

Bump angle = largest force angle;

ELSE judge the direction of F_f

IF the angle of F_f has the same sign with that of its following two forces

Bump angle = − angle of F_f;

ELSE

Bump angle = angle of F_f.

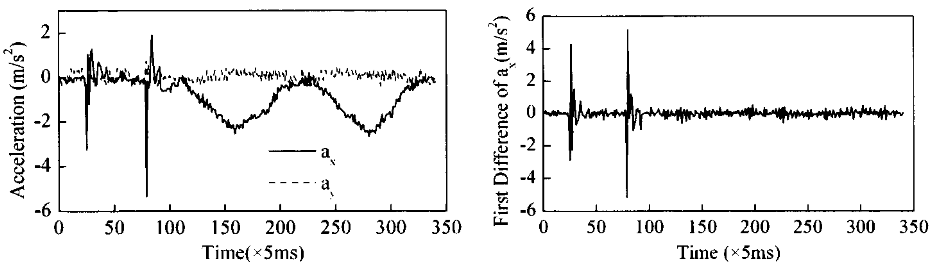
When under violent vibration mode, it is difficult to give an accurate direction angle only from the angle of the vibration force, but the angle of the first vibration force can be taken to show the impact tendency in most cases. Although the direction is not the right one but it is appropriate to lead the robot to a reasonable response.

4. COLLISION SIGNAL SEPARATION

There are two main factors can influence the accelerometer readings besides collision. One is the road. When the robot stays on a slope or rolling road the accelerometer will also output acceleration signals since the accelerometer is sensitive to gravity. The other one is the vibration caused by normal running of the robot as well as the accelerating and decelerating process. The vibration is inevitable when the robot is running, which will induce additional acceleration signals. The normal accelerating and decelerating process will also confuse the acceleration information caused by impact. The robot should firstly judge whether a collision occurs or not from the blending acceleration signals and then separate the collision information for further analysis.

4.1. **Signal separation on rolling road.** When the robot stop on a slope or running on rolling road the accelerometer may also return acceleration readings even no impact happens, so the robot has to make a decision whether an collision occurs and how strong is the acceleration signal.

The acceleration signals induced by impact and rolling road are shown in Fig.3(a), the left two sharp peaks represent two knocks on the robot. Since the knocks are from front to back there are only obvious acceleration fluctuations on a_x. The right two peaks are to simulate running on a rolling road. The vibration intensity of acceleration signal is the main difference between impact and rolling road. Since the difference between two adjacent acceleration points in road signals is much smaller than that in collision signals, the first order difference of the signal can clearly describe the



(a) (b)

FIGURE 3. Acceleration signal caused by impact and rolling slope and the first order difference processing of the signals

difference of these two type signals. Fig.3(b) is the result of first order difference of the signal according to (4.1).

$$a_{di} = a_i - a_{i-1}, \tag{4.1}$$

where a_i is the acceleration reading at time i, and a_{di} is the first order difference of a_i. From Fig.3(b) it is easy to identify if there is an impact by a suitable acceleration threshold. In the paper the threshold is taken as 1.5 m/s^2 to ignore a small bump. Thus the robot will not think he is knocked when running on a slope or rolling road.

When the robot stops on a slope and impacted by other moving object, the accelerations that the robot detects are just like that on the horizontal ground but all the signals are added a base. So the first order difference can also do its work, and a suitable median filtering will remove the impact information with the slope signal left. Then the pure collision signal may be obtained by subtract the slope signal from the total accelerometer readings. Section 4.2 will gives more detail.

4.2. **Signal separation on normal running state.** The continuous acceleration fluctuation will happen when the robot is moving. The acceleration signal will be induced by vibration of robot itself, the rough road and the velocity changing of the robot. In order to correctly judge the occurrence of an impact and evaluate the impact direction, the first task is to distinguish an impact acceleration signal from the normal running acceleration signal, and then the impact signal should be separated correctly to decide the collision direction.

A period of acceleration fluctuation can be seen in Fig.4(a), in which the robot keeps moving and knocked twice by a ball from front to back. To illustrate more clearly only signal of a_x is showed and processed in the figure. It may not be reliable to judge the happening of an impact only by acceleration value for some accelerations in normal running are large enough to be taken as an impact as shown in Fig.4(a). To accurately perceive a knock and separate the acceleration quickly, a detecting window of seven points are designed to act continuously on the acceleration signals, in which the data are filtered with a 7 points median filter, the average of the 7 points are calculated and the variance of the middle point of the window is obtained.

From observations there are no more than 3 large accelerations appear adjacently when a collision occurs, which means a 7 points median filter can remove the acceleration peaks caused by the impact, and the remain data can be seen as the normal running result. The detecting window is as follow:

a_i	a_{i+1}	a_{i+2}	a_{i+3}	a_{i+4}	a_{i+5}	a_{i+6}	a_{i+7}

Where the acceleration a_{i+3} is the key point to be detected, the median filtered value of a_{i+3} is determined by

$$a^f_{i+3} = \text{ Median value } \{a_i \dots a_{i+6}\}. \tag{4.2}$$

So the average value of the 7 points after filtering represents the running acceleration at the time, which is obtained by

$$a^a_{i+3} = \frac{1}{7}\sum_{k=0}^{6} a^f_{i+k}. \tag{4.3}$$

In order to calculate a^a_{i+3}, all the 7 accelerations in the window should be evaluated first, and to obtain a^f_{i+6}, the data to a_{i+9} should be collected, which means the impact detection is not in real time but delays for 3 sampling periods. Since the sampling period in this system is 5 ms, the delay can be ignored compare to the much longer response time.

The actual impacting accelerations can be obtained by subtract the average value from the original data with (4.4).

$$a^b_{i+3} = a^f_{i+3} - a^a_{i+3}. \tag{4.4}$$

To set up a criterion of recognizing a collision, the variance of the middle point in the window are calculated in (4.5), and the corresponding curve is shown in Fig.4(b), in which the variance of collision acceleration is much large than that of running ones and can easily be recognized with a suitable threshold.

$$E_{i+3} = \left(a^f_{i+3} - a^a_{i+3}\right)^2. \tag{4.5}$$

A threshold of 4 is chose for this robot system. Certainly the size of detecting window may change according to the acceleration character of different system. The real collision acceleration signal is shown in Fig.4(c), which can be processed further to obtain impact force and direction. For the case that the robot moves on a slope and knocked by an object, the method in this section is also applicable. The information that the accelerometer detects will include acceleration caused by slope, the impact signal and normal moving acceleration, which has an additional acceleration base

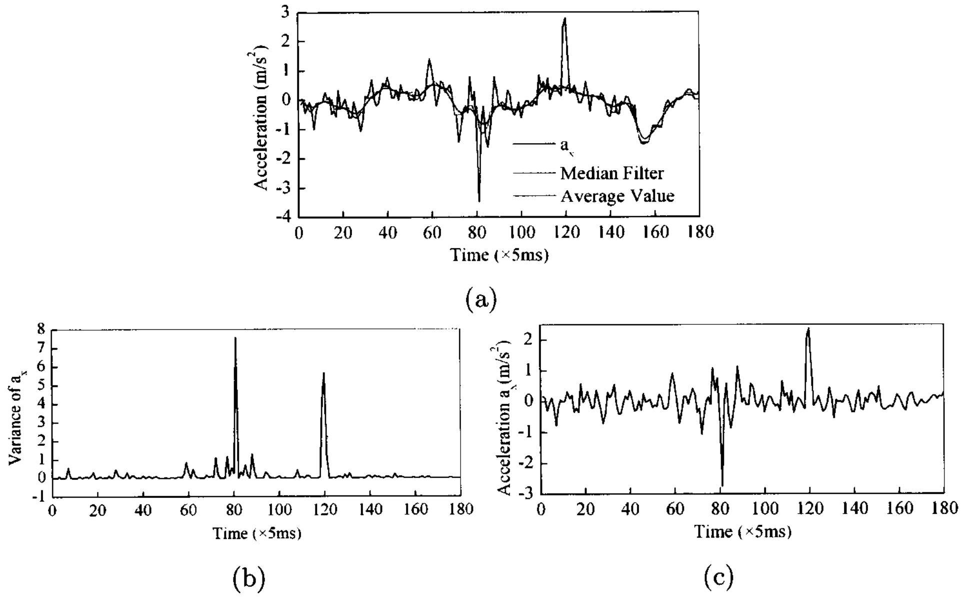


FIGURE 4. Collision signal separation from normal running vibration

larger than the signal moving on horizontal ground. The acceleration base can be taken as a constant in 6 sampling periods, so the detecting window will also do its work on this case, the acceleration base from slope will be remove when subtract the average value of the filtered window from the original information to obtain pure collision signal. The principle of variance E_{i+3} is just like the first order difference process but the value is enlarged.

The above mentioned case is when the robot is knocked along x direction, when the robot is knocked from other directions both the acceleration a_x and a_y will fluctuated violently, the impact signal on y direction can be processed with the same method at the same time. After the pure collision signals are separated from the blending acceleration the direction of collision as well as the impact force can be calculated as discussed in section 3, and then the robot should make a response to the impact.

5. RESPONSE TO COLLISION

Since the impact direction detected with this method is not very accurate, and it also do not need very accurate impact information to implement good response. To simplify the responding mode and weaken the responding error, eight equal zones are divided around the robot as shown in Fig.5. Each zone corresponding to one responding mode that takes the bisector of the zone angle as the impact direction. For example in Fig.5, the detected impact force is F_b, the direction of which belong to zone B, so a response will take place as if a force F_B act on the robot with the direction angle of 45°.

The responding intent is to escape from contact as soon as possible and then turn back to search the attacking object. When impacted by force F_b, the robot will rotate clockwise at same time run forward since the gyration center is on the mid-point of the front wheel axis 50 *mm* before geometrical center. Such a motion will quickly break away from the contact of impacting object from robot tail. When robot runs forward for 500 *mm* it has kept away from the impact path, then the robot wants to see what is the aggressor, so it rotates back at the current position until the camera point to the position where the impact occurs. Now the robot can rotate its camera to search the object. The pan angle of the vision is ±90° and the tilt range is ±25°. The robot needs to remember its position and orientation as well as the impact point when impact happens in order to search the object subsequently. Seen in Fig.6, the robot first runs from o to o' to avoid further impact and then it rotate back to search the aggressor. In fact when find the object we make the robot run after the object and catch it in our experiment.

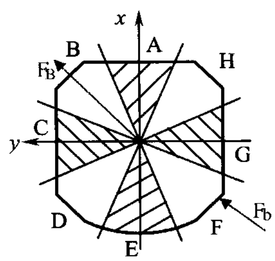


FIGURE 5. Eight reacting divisions of the robot

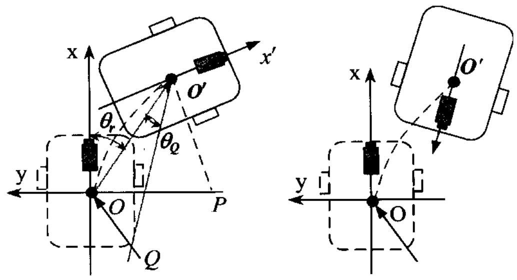


FIGURE 6. Respond to bumping force

6. EXPERIMENT AND DISCUSSION

In order to verify the validity of the method in detecting impact direction and the ability of making a reasonable response, the experiments are carried out. First the robot stays statically on the ground and knocked by a soft ball with different modes to see the ability of judging impact direction and make a response. Then the robot is set to different running state to show the effect of identifying a collision and separating the pure impact signals.

The robot is firstly knocked from different direction and on different region by a ball and then different types of objects are used to knock the robot to see the robustness. The experiment is carried out in a room, the robot keeps still and then a soft volleyball is rolled quickly toward the robot in the direction of 0°, 45°, 90°, 135°

and 180°. These directions are chosen for the shape of the robot body provides the planes with the normal direction of these angles. When the ball knocks these planes vertically it is thought the impact along the mentioned directions. All impacts in the experiment are performed by the same person but without a strict restriction of force value. Thus we can find when the detected resultant force is less than $20N$, the detecting error growth rapidly.

The knocks are carried out 30 times in each direction. Table 1 shows the result of impact detection and response. There are two cases for knock in 90°, the item 90A in Table 1 means the ball knocked the robot on the place behind the wheel, and 90B means the ball knocked directly on the end surface of the wheel. The main difference between the two cases is that the 90A knocked on the plane yet the wheel end surface is not an absolute plane. So in case of 90A a more accurate impact direction may realize than in 90B, on the other hand a knock on the back part (in case 90A) of the body will induce an additional swing around gyration center yet the knock on wheel can only induce lateral vibration.

Table 1 shows that the impact 0° on 180° and can be detected better, and the best detection occurs on 0°. The main reason is that the wheel can easily rotate forward or backward, when knock from 0° or 180° direction the vibration complies with the motion tendency, so the vibration period is short and the knock direction can be reflected by very limited vibration force, which make the detection easy with more accuracy. In the experiment, usually one of the first two resultant force's direction is the collision direction. To check the detecting rate of collision direction, an error tolerance of 15° is set. Since it is not necessary to obtain accurate impact direction, the direction within 15° error limit may achieve the right response. According to this criterion, the knock on 0° can be detected completely and the detecting rate of 180° knock is 80%. In despite of the detecting rate of only 60%, the detection of 45° is thought good. For the data fluctuation is relatively small although the average absolute error of 10.6° is not low. The reason is that when knock from 45° direction, the force component of x direction may induce larger vibration than that of y direction although their values are the same, thus the acceleration of a_x is a little larger than a_y to make the angle of resultant force smaller than 45°. But the result

TABLE 1. Analysis of bump detection result

	Bumping direction angle (degree)				
	0	45	90A	90B	180
Mean value	3.9	35.6	78.0	92.9	170.3
Absolute error	3.9	10.6	12	2.9	9.7
Detecting rate (%)	100	60	53	50	80

shows that the direction extracting method is available and the further work may be to compensate the acceleration loss on y direction.

On the case of 90A in Table 1, the absolute error is the largest one among these cases, and the mean value is also smaller than theoretical value, the reason is the same for the case of 45°. When knock on the back of the robot, a swing will happen which will increase the vibration on x direction. If more than one set of accelerometer is installed in the robot the error may be decreased by data processing. The case of 90B just illustrates the problem. When knock on the wheel, little swing happens and the absolution error is small. But such an impact will induce the so-called violent vibration, and the detection of bump direction is not easy. So it can be seen in Table 1 the correct detecting rate is low and a quantity of direction error beyond 40°. To exactly detect such an impact multiple accelerometers will be needed [11, 12]. The knock from 135° is not listed in Table 1, the result of which is much like that of 45° case.

According to the response policy, when robot perceive a knock it should turn back to search the impacting object. In the experiment a ball is used to knock the robot, but the ball will bounce away instantly after knocking, if it rolled a long way because of large knock force, it will be difficult for the robot to find it. But generally without the intense impact the robot will find it with the flexible camera.

After the experiment with ball, we chose another two means to knock the robot, hand and rubber hammer. All the knocks are along 0° direction. When knock with hand the palm fringe is used to knock. The result is seen in Table 2, the ball knocking case shows better detect result than the two others. It seems that a rigid object is easy to induce violent vibration and such will bring more difficulties for bump direction detect. As the hand, it is not easy to control the knock direction than the other two objects.

Another experiment is carried out to verify the ability of robot in separating collision signals, judge the impact direction. The robot is firstly stopped statically on flat, a ball is used to run from 1 m away to knock the robot along x axis, y axis and other direction to show the bump detecting rate, the direction judging rate and the rate of making right response. All impacts in the experiment are performed by

TABLE 2. Analysis of different bumping object

	Type of bumping object		
	Ball	Hand	Rubber hammer
Mean value (degree)	3.9	8.5	10.2
Absolute error(degree)	3.9	8.5	10.2
Detecting rate (%)	100	83	75

the same person but without a strict restriction of force value. Since it is difficult to throw a ball to a robot along exact direction especially when the robot is running, the required impact direction is only a scope. The response of the robot to a collision is also extended to a certain scope.

The experiment results are shown in Table 1. The collision detect rate in Table 1 is the rate that the robot has correctly judged the impact direction in an error of $\pm 15^\circ$. In fact the robot can completely perceive every knock on all the situations, which implies the separating method of impact signal and the impact occurrence judging method is effective. But the impact direction determination is effected by many factors such as the knocking direction, and do not show perfect result. Yet since the response of the robot to bump is not strictly limited to an exact direction angle, the successful responding rate is fairly high.

7. CONCLUSION

It is meaningful for an autonomous mobile robot to detect collision no matter to avoid danger or to be a communication way to accept instruction by pat. It is may be easy to perceive the happening of an impact but will be difficult to determine its direction with accelerometer. The paper manage to detect collision on complex moving situations and make reasonable response with only one set of 2-dimensional accelerometer, which greatly simplify the traditional collision detection with bumping belt and can detect the impact from any direction. The experiments show that the robot can identify an impact from blending acceleration signals with first order difference and the detecting window, with the extracted pure collision signal the robot can make reasonable response in most cases, especially when the knock is from front to back or from back to front. But some difficulties are also exposed. In order to implement better detection in more severe conditions, more accelerometers are needed. The future study will focus on multiple accelerometer detection and make use of other Artificial intelligence techniques such as neural network to evaluate the impact force.

REFERENCES

[1] S. Yuan, Q. Xu and L. Zhang, Experiments on active vibration control of a flexible four-bar linkage mechanism, *ASME Journal of Vibration and Acoustics*, 122:82–85, 2002.

[2] J.L. Westen and D.H. Titterton, Modern inertial navigation technology and its application, *Electronics and Communication Engineering Journal*, 12:49–64, 2000.

[3] A. Martinelli, The odometry error of a mobile robot with a synchronous drive system, *IEEE Trans. on Robotics and Automation*, 18:399–405, 2002.

[4] J. Borenstein and L. Feng, Measurement and correction of systematic odometry errors in mobile robots, *IEEE Trans. on Robotics and Automation*, 12:869–880, 1996.

[5] J. Palacin, X. Lasa and S. Marco, Straight-line path following in cleaning robots using lateral ultrasonic sensors, *Proc. of the IEEE Instr. and Meas. Tec. Conf*, 2:1484–1487, 2003.

[6] J. Palacin, T. Palleja, I. Valganon and R. Pernia, Measuring coverage performances of a floor cleaning mobile robot using a vision system, *Robotics and Automation, Proceedings of the 2005 IEEE International Conference*, 4:4236–4241, 2005.

[7] W.T. Ang, P.K. Khosla and C.N. Riviere, An intelligent hand-held microsurgical instrument for improved accuracy, *Annual Reports of the Research Reactor Institute, Kyoto University*, 4:3450–3453, 2001.

[8] H. Yoshihiro, Y. Kohei and N. Kentaro, Development of a hand-held sensor probe for detection of sound components radiated from a specific device using surface intensity measurements, *Applied Acoustics*, 65:719–735, 2004.

[9] A. Talukder, R. Manduchi, A. Rankin and L. Matthies, Fast and reliable obstacle detection and segmentation for cross-country navigation, *Proc. IEEE Intelligent Vehicle Symposium*, 2:610–618, 2002.

[10] L. Seungbae, N. Gi-Joon, C. Junseok and H. Kim, Two-dimensional position detection system with MEMS accelerometers, readout circuitry, and microprocessor for padless mouse applications, *IEEE Trans Very Large Scale Integr VLSI Syst*, 13:1167–1178, 2005.

[11] J.G. Garcia, A. Robertsson, J.G. Ortega and R. Johansson, Sensor fusion of force and acceleration for robot force control, *International Conference on Intelligent Robots and Systems*, 3:3009–3014, 2004.

[12] J.J. Crisco, J.J Chu, and M.R. Greenwald, An algorithm for estimating acceleration magnitude and impact location using multiple nonorthogonal single-axis accelerometers, *Journal of Biomechanical Engineering*, 126:849–854, 2004.