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Climbing Service Robots for Improving Safety in Building Maintenance Industry

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1. Introduction

Tall buildings and hazardous utilities require regular inspection and maintenance to comply with the ordinance, and to ensure the integrity and safety. The traditional manual inspection and maintenance on tall building normally requires the installation of expensive scaffoldings or gondolas in which human operators need to work in mid-air and life-threatening environment. Moreover, in some hazardous industries, such as nuclear, chemical and power generation, these maintenance tasks can be harmful and hazardous to human life and health. On the other hand, the reliability of the manual inspection approach is questionable because human judgement is always subjective. Consequently, the poor inspection result will deduce either excessive or inadequate repairing work that is undesirable in term of costing and safety.

Over the years, a number of climbing robots have been developed for various building inspection and cleaning applications (Tso et al., 2000; Tso et al., 2001; Zhang et al., 2001; Hillenbrand et al., 2001; Sattar et al., 2001; Bahr & Yin, 1994; Wang & Shao, 1999; Minor et al., 2000; Luk et al., 2005; Luk et al., 2006). Beside the above development, the authors have also been requested by industry to develop a number of climbing robots cater for various maintenance tasks. These tasks are usually difficult and costly to be achieved by manual approaches. As buildings in many metropolitan cities like Hong Kong are getting taller and taller, the public concern for the safety of high-rise buildings and large structures is rising. Recently, the Hong Kong Housing, Planning and Land Bureau has just finished a public consultation on mandatory building inspection and intends to pass a legislation to enforce the mandatory inspection of all tall buildings aged 30 years or above. Other cities may have similar requirement in the future. As a result, there will be more and more demands to improve the accuracy and efficiency of building inspection and maintenance processes. It is a matter of fact that application of climbing service robots is one solution to service this purpose.

In this chapter, WIC, SADIE and Robug III climbing robots developed by the authors will be described. WIC is a gondola-based climbing robot developed for inspecting tile-walls of high-rise buildings in Hong Kong. SADIE is a climbing robot with seven non-articulated legs developed for carrying out ultrasonic inspection and surface preparation inside reactor cooling gas ducts at Sizewell 'A' Power Station. Robug III is a walking and climbing robot

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with eight articulated legs developed for working in unstructured environment. As many high-rise buildings especially in Hong Kong use tiles for protecting and decorating wall surfaces, it is therefore essential to develop a cost effective and accurate method for inspecting tile-walls. In this chapter, a novel automatic impact-acoustic method for tile-walls inspection is described. As gait generation is one of the important issues for robots with multiple articulated legs. In this chapter, an GA (Genetic Algorithms) based gait generation algorithm is discussed. As most of these climbing robots are teleoperated in outdoor and dirty environments, a water-proof console without any key or joystick is desirable. Therefore, the development of a low-cost data glove system for controlling climbing robot will also be reported with the details of the glove structure, and the robot instruction by hand-gesture recognition method.

2. WIC Robot for Tile Wall Inspection

Facades of many concrete high-rise buildings in Hong Kong are tiled or similarly clad for decoration and weather protection. Due to factors such as uneven temperature distribution, acid rain, and poor initial workmanship, these elements tend to debond before the end of the expected building life. In order to prevent loose tiles from falling and causing injuries, tile debonding inspection is frequently required. The manual impact-acoustic method commonly used involves impacting every tile with a standardized hammer and listening to the tone-feedback. The shear size of the building facades (there are approximately 50,000 high-rise buildings in Hong Kong alone) and the necessity of impacting every tile at multiple characteristic locations make this task fatigue and error-prone. It is also hazardous, requiring work in mid-air at high altitudes. The quality of the outcome is questionable in terms of the consistency of the inspection coverage and the workers' subjectivity in distinguishing the difference in the tone-feedback of impact sounds from the bonded and debonded tile segments during countless hammer-strikes. Yet, even a single 250 g tile falling from the 10th floor height can gain a deadly momentum of 60 Ns at the ground level.

In order to improve the efficiency, accuracy and safety of this hazardous and markedly fatigue-prone manual inspection work, many other methods such as impact-echo, ultrasonic and Infra-red thermographic methods have been tried. However, impact-echo and ultrasonic methods are ruled out because of the need to maintain a constant contact between the sensor and the target wall surface, which is difficult or inconvenient to be realized at heights and on large testing areas. Meanwhile, other non-contact techniques such Infra-red thermographic method are too environment-sensitive and generally too expensive. As a result, the NDT (Non-Destructive Testing) technique preferred by the Housing Authority is still the impact-acoustic method. In order to automate and enhance the accuracy of this NDT technique, a robotic-NDT system called WIC robot has been designed and constructed. The system mimics the standardized manual impact-acoustic inspection method.

2.1 WIC Basic Robot Structure

The tile-wall inspection robotic system consists of three main parts as indicated in Fig. 1 and Fig.2: 1) a climbing robot equipped with an impact-acoustic NDT device for inspection, 2) a ground station with a cable driving mechanism and control console, and 3) a supporting structure at the building roof. By design, the robotic system adopted a similar mechanism as those used in common industrial gondola for building maintenance but with additional

capability of climbing up and down the building and performing inspection of the entire wall surfaces automatically. The robot system is much lighter than ordinary industrial gondolas and hence it is much easier to install. Fig. 3 shows the robot carrying out an inspection operation on a high-rise building.

Figure 1. The basic setup of the WIC inspection robot system

Figure 2. The climbing robot with its ground station and control console

Figure 3. The WIC robot system carried out inspection on a high-rise building in a public housing estate

2.2 Impact-Acoustic Non-Destructive Test Device

The impact-acoustic non-destructive test device consists of: a steel sphere of diameter 12mm, an impactor which is a linear solenoid actuator for pushing the steel sphere to generate the required impact force, pre-amplifier module, ADC card with 40KHz sampling frequency, and a highly directional microphone (see Fig. 4 and 5). The main advantage of this method is that the impacting device and microphone need not be coupled onto the wall surface continuously. This is of great convenience for the robot system working at heights. Moreover, it takes less time and effort to perform inspection on large-area of wall surfaces.

Figure 4. The system block diagram of the impact acoustic inspection device

Figure 5. A close-up view of the inspection system in operation

2.3 Impact-Acoustic Non-Destructive Test Device

It can be readily shown that the fundamental frequency of flexural resonance of the tile increases with diminishing size of the void underneath it – for the same tile thickness. The impact-generating nature of the problem is represented by a two-degree-of-freedom spring-mass system (Fig. 6). One spring with stiffness K_f represents the tile deflection, and the other spring with stiffness K_c represents the contact movement. The two masses, M_2 and M_1 , represent the tile and the impacting sphere, respectively.

Considering the energy distribution in the system, the original kinetic energy of the sphere deforms the structure during the impact. Assuming that the structure is elastic, as it reaches its maximum deformation the velocity of the sphere is zero and all of the initial kinetic energy has been converted to the energy stored by the deformation of the structure. Therefore, ignoring the shear and membrane components of structure deformation, the energy balance equation can be shown in (1).

$$E_{sum} = \frac{1}{2} M_1 v_0^2 \approx E_f + E_c = E_f + E_{c1} + E_{c2} \quad (1)$$

where v_0 is the initial sphere speed, the subscripts f, c refer to the energy stored in the elastic deformation of the structure and sphere indentation in the contact region (c_1 pertains to the sphere and c_2 to plate).

Figure 6. The spring-mass model of impact

It can be shown that the ratio of energy converted into flexural vibration depends on the thickness and radius of the plate. In the tile-wall structure, the thin tile layer caused by serious bonding degradation has small thickness and effective stiffness, leading to much stronger flexural vibration under impact compared to a solid tile-wall. Based on acoustics theory, the intensity of sound radiation is proportional to the vibration energy. Thus, the intensity of sound excited by flexural vibration after the impact can be used as a crude indicator for the bonding-integrity of the tile-wall.

According to theoretical analysis for a degraded tile-wall, the thin tile layer formed by a void separation underneath will lead to the absorption of most of the kinetic energy of the impacting sphere through the flexural vibration mode of the tile. For a solid tile-wall, however, the loss of kinetic energy of the sphere is very small.

The strength of free vibrations of the sphere caused by impact indentation is also affected by the *vibration energy factor* $\lambda = E_f / E_{sum}$ (Christoforou & Yigit, 1998). As a result, the relative intensity of sound radiated from the vibrating sphere and plate can indicate the integrity status of the tiled structure.

R_{ps} is defined as the ratio of sound intensities from the sphere and plate,

$$R_{ps} = \frac{I_{plate}}{I_{sphere}} = Q_{const} \cdot \left(\frac{1}{1 - \lambda} - 1 \right) \quad (2)$$

where Q_{const} is a constant representing the properties of the plate and sphere materials. Because the solid tile wall is generally over 20 times thicker than the thin layer of debonded tiles, the ratio of the sound intensities from the sphere and plate after impact R_{ps} will appear significantly different in the presence of debonding. Using this impact sound method, the need to use coupling agents or to apply high pressure on tile-walls can be avoided.

2.4 Void Size Versus Fundamental Frequency

By representing a tile with the void underneath as a thin rectangular plate of thickness h with simply supported edges, it has been shown analytically that the fundamental

frequency of flexural resonance increases with diminishing size of the void (Rossing, T. D. & Fletcher, N. H., 1994). Moreover, the shape of the void also has a significant influence on the fundamental frequency.

This finding forms the theoretical basis for operation of the robotic-NDT system shown in Fig. 4 and 5. The system performance has been tested in practice on solid and degraded (with various debond size) tile-wall surfaces. In Fig. 7, a stable spectrum peak at about 6.7 kHz is attributed to the free vibration of the steel ball. Other resonance frequency components are caused by flexural vibrations of the tile structure with the void. It is seen that with decreasing void dimension the measured fundamental frequency increases from about 300Hz to 2.3 kHz, 2.9 kHz and 4.0 kHz. The measured and theoretical (with assumed parameters) fundamental frequencies for 7 cases with different void sizes in the specimens and site tests are given in Fig. 8.

Figure 7. Impact sound feedback spectrum (a) from a solid tile wall, (b) from a tile wall with the debond size 160mm×114mm, (c) with a debond 120mm×114mm, and (d) with a debond 80mm×114mm

Figure 8. Theoretical and measured fundamental frequency versus debond size

The deviations between the theoretical (based on assumed geometry) and measured values are caused by many factors. Background noise and microphone distortions are just some of the disturbance effects. While the system therefore can provide only a rough estimation of the void size under individual tiles, there is little difficulty in identifying whether there is a void or a solid bond underneath.

3. SADIE Series of Climbing Robots

Figure 9. SADIE Robot and Its Tool Packages

Figure 10. SADIE Control Console

The SADIE (Sizewell A Duct Inspection Equipment) robot is commissioned by Magnox Electric plc in the UK to perform non-destructive testing of various welds on the main reactor cooling gas ducts at Sizewell 'A' Power Station. The robot and its control console are shown in Fig. 9 and 10 respectively. As an important part of the requirements, the robot is required to climb upside down at the top of the duct to inspect some of the welds. It is therefore necessary to develop a force controlled foot change over sequence in order to prevent the robot from pushing itself off the duct surface by exerting excessive force.

The welds which required preparation and inspection are RC 24, RC 25, RC 26, SC 12, M 1, L 1 and L 2. These are shown in Fig. 11.

Figure 11. Sizewell A Air Cooling Duct

3.1 Grinding Application

During the initial design of the SADIE robot, it has been identified that some of the welds which require inspection are obscured by ladder brackets. As a result, SADIE is required to carry a specially designed grinding package to remove those ladder brackets. Since the ducts are connected directly to the reactor core, it is essential that the ladder brackets should not be allowed to fall down the duct to endanger the reactor. A special grab mechanism is therefore incorporated on to the cutting tool for recovering the cut ladder-brackets. A 3D drawing is shown in Fig. 12.

The ladder bracket removal package (LBRP) is mounted on the front frame of the vehicle and consists of two main elements - an air powered disk grinder mounted on a cross-feed mechanism, and a pneumatically operated grab mechanism.

The grinding tool and the cross-feed mechanism are hinged on the axis of the cross feed. A pivot allows the grinding tool and the cross feed to rotate on the cross feed axis. These degrees of freedom allow the grinder to follow the curves in the duct, providing compliance with the contours of the surface. This compliance is stabilised by ball transfer units on either side of the grinder disk and a centrally positioned pneumatic cylinder applying a steady force ensuring the transfer balls stayed on the surface. The pneumatic cylinder also provides lift to allow the grinder to be raised off the surface when manoeuvring into position. The cross feed is driven by a force controlled pneumatic cylinder.

The grab mechanism is positioned above the cross feed. The ladder bracket is held in a U bracket with a spring return piston actuating a bolt through the hole in the ladder bracket. The arm is actuated using additional pneumatic cylinders to provide a lift/lower and extended/retract functions.

Figure12. Ladder Bracket Removal Tool Package

The mechanism uses a camera for primary observation and micro-switches to indicate the ends of the cross feed travel. The cross feed actuators utilise a differential pressure sensor to provide force sensing.

To allow more than one ladder bracket to be removed per deployment a ladder bracket box is designed. This box is mounted on the deployment scoop. Its design incorporates a hinged lid which is kept shut with a spring. The lid traps the ladder bracket within the box.

3.2 Non Destructive Testing Application

To inspect the welds Ultrasonic scanning is used. An inspection tool has been designed by Magnox Electric for SADIE which could carry the Ultrasonic transducers. An array of sensors are used in what is known as the probe pan. The probe pan uses a gimbal joint to ensure a good contact with the surface and it scans across the weld by a servo controlled linear axis mounted across the front of the vehicle.

The probe pan contains a system for squirting ultrasonic couplant around the transducers so that good quality signals are produced. The ultrasonic couplant is a water based gel to avoid the need for cleaning the gel after the inspection.

3.3 Deployment

A major part of the operation is the deployment of the vehicle. A specially designed deployment system is constructed which comprises of a framework and a radiation containment unit. This carries the Vehicle Deployment Scoop, deployment cable and its associated winch and the umbilical management system. The Vehicle Deployment Scoop is a four sided box structure, on which the vehicle is positioned prior to deployment. Its angle is controlled by a winch drive and cable.

The vehicle is placed on the Deployment Scoop and the vacuum is applied to the gripper feet. Having moved the frame towards the duct, the platform and vehicle are inserted through the Duct access port and when the appropriate position is reached, the Platform will be rotated to a vertical axis. The vehicle is then either be driven off or lifted off (having

first removed the gripper feet vacuum) by the umbilical/retrieval wire onto the landing zone, at the sloping surface of the duct bend.

Retrieval is a reverse of this sequence, driving the vehicle up the duct until it is positioned on the scoop. Vacuum is then applied to cause the vehicle to attach itself onto the plate. A rotation of the scoop when it reaches the man door is executed to allow retrieval of the vehicle.

4. Robug III Intelligent Legged Climbing Robot

The range of applications for legged vehicles is much greater than for traditional wheeled/tracked vehicles. The disaster at Chernobyl has dramatically highlighted the need for a versatile mobile robotic vehicle for use in unstructured hazardous environments. Robug III is an example of one such vehicle that has been developed for the specific purpose of remote inspection and maintenance in places where human workers cannot access or work safely. In the event of an accident, when the normal routes of access may be blocked, the robot may be found useful to gain access by climbing over walls and obstacles.

Figure 13. Robug III robot

Robug III (see Fig. 13) is a compact and powerful teleoperated walking and climbing robot with articulated limbs (see Fig. 14). The vehicle body is 0.8m long by 0.6m wide by 0.6m high, with the eight articulated leg modules each 1m in length, consisting of 3 links constructed from high strength composites. Each leg module has its own microprocessor and is driven by a pneumatic drive system at 1300kPa to achieve a high power-to-weight ratio and inherent compliance; these qualities are important in walkers because they allow for the development of lightweight machines without compromising the payload capabilities, while minimising the possibility of damage when operating in unstructured environments. The pneumatic drive system allows for the attachment of vacuum gripper feet at the end of each leg for climbing. A redundant joint is included on each limb for climbing and crossing between various surfaces whilst at the same time keeping the robot body close to the terrain surface.

Figure 14. Robug III leg layout

The genesis of the robot structure is based on the emulation of arthropod walkers and climbers; in particular the entomological and crustacean groups. Indeed, many of the design features have been inspired by nature - researchers working in the area of legged robotics traditionally look toward the natural world for inspiration and solutions, reasoning that these evolutionary solutions are appropriate and effective because they have passed the hard tests for survival over time and generations. Robug III has adopted the “crab walking” strategy because of faster walking speed and the requirement of the robot to be able to crawl through a narrow passage, however, the robot is also capable of using a longitudinal walking gait (insect gait). The central low-slung body offers increased intrinsic stability while sideways walking minimises the problem of legs tripping over one another. Designing and developing a legged robot capable of walking over a variety of terrains efficiently and autonomously is a challenging task and involves expertise from a wide range of disciplines.

4.1 Adaptive Gait Generation

The time-space co-ordination of the motion of the Robug III legs involves a decision regarding what leg should be lifted or placed. The means by which the decision is made is known as the gait strategy. In the extreme case this decision must be made with regards to factors such as the condition of the terrain, stability requirements, ease of control, smoothness of body motion, speed requirements, mobility requirements and power consumption. This presents a highly complicated problem which is most commonly reduced by concentrating on performing smooth walking and climbing motions over variable terrain while maintaining vehicle stability and velocity, as is the case here.

In this section we show how a genetic algorithm can be applied in the context of the gait models, in particular it is shown that walking gaits with optimal or near-optimal stability margins can be obtained by using GAs to facilitate the derivation of the optimal gait parameters. To help the understanding, gait diagrams will be used to provide a graphical representation of the gait characteristics over time. Gait diagrams use black lines to denote when the leg is in contact with the terrain and blank areas to represent when the leg is not in support. The legs are numbered so as all even-numbered legs are positioned on one side of the body whilst odd-numbered legs are on the other side.

GAs are particularly good search and optimisation techniques based on the biological evolutionary process that have found widespread use in robotics and control. In this example two tests were conducted using a GA to find gaits which offered maximum stability for the robot walking over flat terrain in a normal operating conditions and when

one leg was made inoperative. The fitness function of the GA was based on the stability of the robot evaluated over a set walking period. The individual chromosomes of the GA were encoded to represent the co-ordinating parameters for each leg, namely the phase and duty factors, that describe the leg support periods and time relationships between the legs which thus define the basic walking motions of the robot.

Fig. 15 depicts the results for the first test and shows the derived walking gait for the fully operational robot, which can be seen to be approximately tetrapodal. This type of gait has been shown to exist in nature and is characteristic of the walking behaviour of the ghost crab over flat terrain (Burrows & Hoyle, 1973)

Figure 15. GA-generated walking gait for normal walking on a flat surface

For the second test we assumed the robot to have an inoperative limb, which could have been caused by damage or a system failure. In this case leg 0 was made inoperative. Close inspection of the resulting gait diagram in Fig. 16 shows that a tetrapod class gait has been evolved that co-ordinates legs 1 and 2 (the most critical legs in this case due to the loss of leg 0) so that the possible situation of both legs being in transfer state at the same time is eliminated, thus minimising the loss of stability incurred by the broken leg.

Figure 16. GA-generated walking gait for when one leg is made inoperative

The GA-based gait generation system has been proved capable of deriving walking and climbing gaits for Robug III that are suitably adapted to a wide range of terrains and the

scenarios therewith. The automatic generation of optimal walking and climbing gaits not only provides a foundation for efficient robot motion but presents a base in which we can learn ideal walking behaviour patterns and gain valuable knowledge with which to develop the walking and climbing control mechanisms.

5. Teleoperation by Low-cost Data Glove System

The design concept of a gesture-recognition based data glove system for controlling the robots will be discussed in this section. The gesture-recognition technique is based on the well-known hidden Markov model (HMM), and the data-glove consists of a pair of orthogonal 2-D acceleration sensors that can measure acceleration in the x-y-z directions. Since the gesture is recorded in the form of noisy acceleration data, wavelet-filtering technique is applied to smooth the data, and the velocity is calculated by integrating the smoothed acceleration data. The velocity profile is then transformed by the short-time discrete Fourier transform (STDFT) so that the time-domain profile is represented by a sequence of frequency spectrum vectors, which are more suitable for shape comparison. After the spectrum vector units are quantized into a finite number of symbols called observation sequences, it can be modeled and represented by HMMs. Then the gesture comparison and recognition is done by evaluating the observation sequences by all HMMs used to represent all the selected prototype gestures.

5.1 Design of a Low-cost Gesture Capturing structure

The hand-motion capturing system consists of a host computer, an 8-bit microcontroller board, and a data glove as shown in Fig. 17. The accelerometer chips on the data glove convert motion information to electrical signals. The microcontroller board processes the electrical signals, transforming them to 8-bit data. The host computer implements the data analysis algorithms for gesture recognition.

Figure 17. Motion-capturing data glove structure

The accelerometer chip (ADXL202) is a dual-axis acceleration measurement device built on a single monolithic IC. For each axis of measurement, an output circuit converts the analog signal to a duty-cycle modulated digital signal that is ready for micro-controller TTL input. The accelerometer is capable of measuring both positive and negative accelerations up to effectively a maximum level of $\pm 4g$. The micro sensor is suspended on polysilicon springs on the surface of the wafer. Deflection of the structure is measured using a differential capacitor that consists of two independent plates and central plates attached to the moving mass. The fixed plates are driven by two square waves, which are 180° out of phase. Acceleration will deflect the central plates and unbalance the differential capacitor, resulting in two output square waves whose amplitudes are proportional to the acceleration in the two directions. The acceleration direction is recognised by the phase difference of the two output square waves. As one sensor provides two-directional information, a pair of

them are applied to record 3-D hand motion, and they are orthogonally mounted on a data glove, as shown in Fig. 18, where two signals are common with the Y-dimension so that either one of the signals is selected to give the information in this direction.

Figure 18. Data glove with two accelerometer sensors mounted on a data glove

Since the hand-motion is recorded in the form of noisy acceleration, the signal is first digitally filtered so that a more accurate velocity profile generated by integration can be obtained. The digital filter applied is based on the wavelet-type Daubechies filter (Strang & Nguyen, 1996), discussed in the next subsection.

5.2 Daubechies Filter Technique

Each acceleration signal is recorded in the form of a time series. A window of length 4, with positive Daubechies distribution, is applied to the time series. The dot product of the window and the time series segment is calculated as the 'average' value of the segment. A second window of similar type but with alternating sign and revised in the Daubechies distribution is applied to the same time segment. The corresponding dot product is regarded as the *detail* value of the segment. Both windows are applied and moved along the whole time series. The resultant *average* and *detail* data series are called the Daubechies wavelet transformation of the original time series. A simple threshold comparison is applied to the *detail* values so that all values below the threshold setting are floored to zero. Then an inverse process of the above wavelet transformation (called inverse wavelet transformation) is applied to the *average* and the modified *detail* values so that the original time series is recovered with unimportant noise removed. The advantage of this filtering technique over the traditional digital filter is a shorter computational time. Since it is intended that the gesture information is based on the velocity profiles, an integration process is next applied to the filtered acceleration data. The gesture recognition by the HMM process is then applied to the 3-D velocity profiles, as discussed in the following subsection.

5.3 Application of HMM to Gesture Recognition

The mathematical background of HMM may be found in (Yang, 1994). It is basically a probability approach to model or represent a gesture by an HMM parameter λ . Before

applying the HMM to recognise a gesture, the gesture input in the form of a 3-D velocity profile has to be preprocessed so that the time domain profile is eventually represented by a sequence of discrete symbols. The first part of this pre-processing stage is called short-time Discrete Fourier transform (*STDFT*) modified from *STFT* (Hlawatsch & Boundeaux-Bartels, 1992). The single-dimension velocity profile of the gesture is first processed increment by increment as shown in (3) below:

$$STDFT_x^{W_h}(i, f_r) = \sum_{i'=0}^{N-1} \left[x_{i+i'-\frac{N}{2}} \cdot W_h\left(i'-\frac{N}{2}\right) \right] e^{-j2\pi f_r \frac{i'}{N}} \quad (3)$$

where r represents the dimension of f , and the velocity profile x_i is multiplied by a moving "analysis window" $W_h\left(i'-\frac{N}{2}\right)$, centered around the time index i , and N is the window width.

This gives in fact a local spectrum vector f of the profile x_i around time index i . The process applies to X, Y, and Z dimension independently, and then the resulting three sequences of spectrum vectors are combined in cascade to form a single sequence of spectrum vectors with higher dimension. The frequency spectrum reflects the shape and amplitude of a short-time portion of the profile. In the second part of preprocessing stage, the frequency spectra are quantized to a limited number of spectrum-vector units. This part is processed differently for modeling and for evaluating the velocity profile. In the case of modeling gesture: the lists of spectrum vectors, transformed from the velocity profile of all possible prototype gestures, are quantized into a finite number of spectrum-vector units. As the quantization is multi-dimensional, it is called vector quantization (VQ). The algorithm chosen is the LBG algorithm (Linde, Buzo & Gray, 1980). The steps are summarized below:

1. Initialization: Set the number of partitions $K = 1$, and find the centroid of all spectrum vectors in the partition.
2. Splitting: Split K into $2K$ partitions.
3. Classification: Accept the k^{th} partition C_k of each spectrum vector, v depending on the specified condition; i.e.

$$v \in C_k \text{ iff } d(v, \bar{v}_k) \leq d(v, \bar{v}_{k'}) \text{ for all } k \neq k' \quad (4)$$

where $\bar{v}_k$ is the centroid vector of C_k and d is a distortion measure to be defined as a general norm.

4. Centroid updating: Recalculate the centroid of each accepted partition.
5. Termination: Steps 2 to 4 are repeated until the decrease in the overall distortion, at each iteration process, relative to the value at the previous process is below a selected threshold. The number of partitions is increased to a value that meets the required level.

After termination, we will have a number of centroids, $\{\bar{v}_k\}$, of all the partitions. These centroids are in fact the spectrum vector units that represent spectrum vectors transformed from all possible short-time portions of the velocity profile. In the case of performing evaluation, the frequency spectra for an unknown gesture are mapped to the prototype spectrum vectors $\{\bar{v}_k\}$. The mapping is based on the minimum-distortion principle, with the distortion measure given by (5) below.

$$d(v, \bar{v}_k) = \|v, \bar{v}_k\| = \sum_{r=1}^R (v_r - \bar{v}_{k,r})^2 \quad (5)$$

where R is the total spectrum vector dimension. After completion of the mapping, the velocity profile is converted to a list of spectrum vectors $\{\bar{v}_k\}$. In the language of HMM, $\{\bar{v}_k\}$ is written as $\{O_k\}$, called the set of observation symbols, which will be sent through the tuned HMM for evaluating the likelihood index which is given by the conditional probability of getting $\{O_k\}$ given the HMM representing a certain gesture.

5.4 Experimental Results and discussion

Figure 19. Five prototype gestures with indications of swinging directions

To demonstrate the application of gesture recognition for commanding climbing robots with the aid of the data-glove and HMM, five prototype gestures are developed; they are [1] BACKWARD, [2] FORWARD, [3] STOP, [4] LEFT and [5] RIGHT, which are shown in Fig. 19. The recorded acceleration profile of a typical STOP gesture is shown in Fig. 20a. After having applied the Daubechies filter process on the raw acceleration data, the resulting 3-D velocity profile, generated by integration process on the filtered acceleration data, is shown in Fig. 20b. The *STDF*T process by (3) is applied to each dimension of the 3-D velocity profile. Three sequences of spectrum vectors are generated; the three sequences of spectrum vectors are then combined to form a single sequence of spectrum vectors with higher dimension as shown in Fig. 21. The spectrum vector units are then quantized into a number

of discrete symbols according to (5). The outlook of the symbol listing is shown in Table 1 below.

Portion index	1	2	3	4	• • •	76	77	78
Symbol index	50	45	52	48	• • •	79	83	96

Table 1 Outlook of the observation symbol sequence representing the sequence of spectrum vectors

Figure 20. Recorded acceleration and generated velocity profiles of a typical STOP gesture

Since the five prototype gestures have been modelled with the described treatment, they can thus be represented by five sequences of observation symbols. For each gesture, the exercise is repeated five times to improve the quality of the prototype. By the principle of trajectory selection reported in (Tso & Liu, 1997), the best exercise is selected to represent the prototype. Since the human cannot repeat exactly the trace of a certain motion, the profile shape may shift somewhat along the time axis even for the same gesture. The time-warping process (Huang et al., 1990) is applied to adjust the time scale to let a sequence of observation symbols from an unknown gesture map to a prototype one. As a dynamic and probability-based time-warping process, HMM is applied to adjust this time scale. The details of the HMM application can be found in (Yang, 1994). To put it simply, the observation sequence of each prototype gesture is represented by its respective HMM parameter λ_i , where $i = 1$ to 5, corresponding to the five prototype gestures. A test gesture is preprocessed by the same treatment as the prototype, and the output observation sequence O_t is evaluated by each λ_i by calculating the conditional probability $P(O_t | \lambda_i)$. The probability values obtained experimentally are (0.16 0.18 0.43 0.12 0.11) after normalization. The test gesture is hence recognized as the third prototype, which is the STOP gesture, because λ_3 is distinctly highest. By using other test gestures for recognizing all the five prototypes, with each type repeated twenty times, the results show that the average successful recognition rate is 95.6%.

Concluding this experimental result, the use of the data glove to instruct climbing robot can achieve the recognition accuracy being better than 95%. In case, there is a wrong interpretation of the gesture instruction, the command indicator will displace the current interpreted result to the operator so that if he/she find that it is not the right instruction,

he/she can repeat the gesture with the data glove in order to correct the wrongly interpreted instruction.

Figure 21. Generated short-time frequency spectrum vectors by *STDFT*

6. Conclusion

Climbing robots for building inspection and maintenance have many advantages over traditional manual approaches because the formers are more accurate and efficient. For certain hazardous industries such as nuclear or chemical industry, climbing robots may be the only means for carrying out the inspection and maintenance tasks as the environments are dangerous to human operators. As a result, climbing robots are becoming more and more popular in doing building maintenance industry in the future.

In this chapter, several climbing robots including WIC, SADIE and Robug III are discussed. These robots have been used in some practical applications before and have proved their usefulness in building maintenance industry. Currently, most of these robots are one-off design so that they are comparatively expensive. Consequently, the applications of these robots are still restricted to tasks which either require accurate inspection results or are hazardous to human works.

In addition to the robots description themselves, this chapter has also discussed a novel automatic impact-acoustic technique for inspecting tile wall. Besides, as Robug III is a walking and climbing robots with multiple articulated legs, it is essential to develop an effective gait generation system to achieve the robot control. Therefore, an GA based gait generation algorithm is also reported. Since most of these climbing robots are teleoperated in outdoor or dirty environment, the development concept of a robust and water-proof control console is also discussed with the details of the robot instruction by gesture recognition.

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Nature has always been a source of inspiration and ideas for the robotics community. New solutions and technologies are required and hence this book is coming out to address and deal with the main challenges facing walking and climbing robots, and contributes with innovative solutions, designs, technologies and techniques. This book reports on the state of the art research and development findings and results. The content of the book has been structured into 5 technical research sections with total of 30 chapters written by well recognized researchers worldwide.

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