ON-BOARD PERCEPTION PROCESSING FOR SPACE ROBOTS

Yasufumi Wakabayashi*, Makoto Miyata*, Takeshi Nishimaki**
*National Space Development Agency of Japan(NASDA), **AES Corporation
2-1-1, Sengen, Tsukuba, Ibaraki, Japan
E-mail : Wakabayashi.Yasufumi@nasda.go.jp
Phone : +81-298-52-2369 Fax : +81-298-52-2415

ABSTRACT

The progress of embedded system technologies in multi-media consumer electronics is likely to advance the perception processing capability in space robots. Small size boards; on which 1M-gate system-ASICs with several 10MIPS MPU core and multiple communication bus controller, and several 10MB memory with various middlewares, is ready for their use in space applications. In this paper, advantages of these technologies and some results of flight and laboratory experiments are discussed.

1. INTRODUCTION

Implementation of perception functions in a robot is divided into two categories; the one is multi purpose type such as eyes (cameras) and ears (pickups), and the dedicated type such as force sensors, rendezvous & docking sensors, 3D sensors. The latter is required in the realtime controlled, robust and heavy-duty applications and is also effective to enhance the robot function in particular applications, though it costs in many points of view. On the other hand, the former is useful to acquire general perceptional information. This paper describes the applications of highly processed perceptional data in section 2, onboard processing visual data in section 3, onboard processing vibrational data in section 4 and onboard processing force data in section 5.

2. APPLICATIONS OF PERCEPTIONAL PROCESSING

Highly processed perceptional data offers robots many advantages in various situations such as measurement, data transfer, inspection / observation and supervision.

(1)Measurement

The usefulness of onboard visual measurement is apparent. For example in ORU exchange tasks, marker-base operation is used with hand-eye / wrist-eye against a dedicated small 3D-marker on the object. In target oriented attitude control in near field rendezvous, tracking-vision technique can be applied. Furthermore, for non-marker objects, pattern-matching technique and stereo-measurement are considered.

(2)Data transfer

Enabling low telemetry rate operation is important, because the necessity of large communication capacity brings considerable penalties to the system. Several 10Kbps rate is a current target for the study, and middlewares such as JPEG, JBIG, MPEG, etc., instead of dedicated LSIs, enable to use selectable image-data-compression depending on particular operation. For realtime applications, the onboard processing is a priority and high quality data is dispensable for operators; therefore, large data such as a fine imagery has to be transferred to the ground during non-realtime operation. Eventually the reduced data rate operation could be realized by adequate compression technique to each task. Furthermore, the compression technique also can be implemented in the internal data transfer in a robot.

(3)Inspection / Observation

Onboard inspection of satellites and/or equipment in orbit and precise observation of specimen in planetary explorations, are key tasks in space robot application. The onboard perception processing can be applied in these tele-science regions. Though the sensors would collect enormous data for high-resolution and sampling terms, the scientists or engineers on ground may need only the remarkable data for them. Eventually pre-processing must be done by on-board for low telemetry rate operation and effective execution of such tasks.

(4)Supervision

NASDA, office of R&D, has been investigating for years the onboard supervision technique. A space robot

Proc. Fifth International Symposium on Artificial Intelligence, Robotics and Automation in Space, 1-3 June 1999 (ESA SP-440)

has to execute a task or an action without any damages. Even without any malfunction in hardware and software system, an action could cause damage when the total situation/condition is misunderstood by commanders, operators and/or computers. The move-and-wait strategy and very low speed operation might be the answer; however the independent onboard supervisor by highly processed perception data could reduce the difficulty of overall recognition of situation and realize more efficient operational scheme.

3.ONBOARD PROCESSING OF VISUAL DATA

A camera system with middlewared JPEG is developed and introduced here as onboard processing of visual data [2]. COMETS(COMmunication Engineering Test Satellite : Data Relay Satellite of Japan), launched on February 1998, has camera system for monitoring the deployment of the large scale deployment structures; the Solar Paddle and the Antenna. This system was developed based on the camera developed for the future use in space robots. The specifications of this camera are shown in TABLE.1. RISC (Reduced Instruction Set Computer) microprocessor of commercial parts is adopted and placed in this control unit. This processor executes the commands from the ground station, creates the telemetries including the compressed imagery data and transfers them to the ground station.

To decrease the amount of telemetry, the imagery data is compressed by JPEG and compression rate can be changed by the command to adjust the quality of the image.

Within the camera head is a 1/3 inch color CCD which has 320 thousand pixels, which horizontal resolution is 480TV lines at non-compression mode. The camera is equipped with many functions such as auto / manual of the electrical shutter, gamma compensation and so on. The size of the camera head is 88(mm)×81.5(mm)×141.7(mm) and that of the camera control unit is 210(mm) × 245(mm) × 113(mm). The weight of the camera head is about 0.9(kg) and that of the camera control unit is about 5.3(kg).

During this mission, a bit-change occurred a few times in a portion of the image data. This anomaly is thought to be SEU (Single Event Upset) which damaged JPEG's restart marker. The camera was operational during the entire mission. The actual imaged picture on the orbit is shown in Fig.1. Development at the embedded processing of visual data is underway adopting pattern-matching for non-marker objects and stereo-measurement.

TABLE : 1 Specifications of COMETS camera system

Item	Specification
Form	Total Pixels : 320 thousand pixels CCD size : 1/3 inch Color CCD
Horizontal Resolution	480TV lines
Image Data Interface	Serial Digital Telemetry Data Rate : 200bps
Image Buffering Capacity	16 Frame (MAX :1.2M byte)
Compression Method	JPEG
Control Function	Camera ON / OFF Compression Rate : 8 levels Electric Shutter : Auto/Manual (1/30～1/10000 second)
Size	Camera Head : (4 head) 88×81.5×141.7 (mm) Camera Control Unit : 210×245×113 (mm)
Weight	Camera Head : 0.9 (kg) ± 10% Camera Control Unit : 5.3 (kg) ± 7%
Power Consumption	Camera Head : 1 (W) Camera Control Unit : 12 (W)

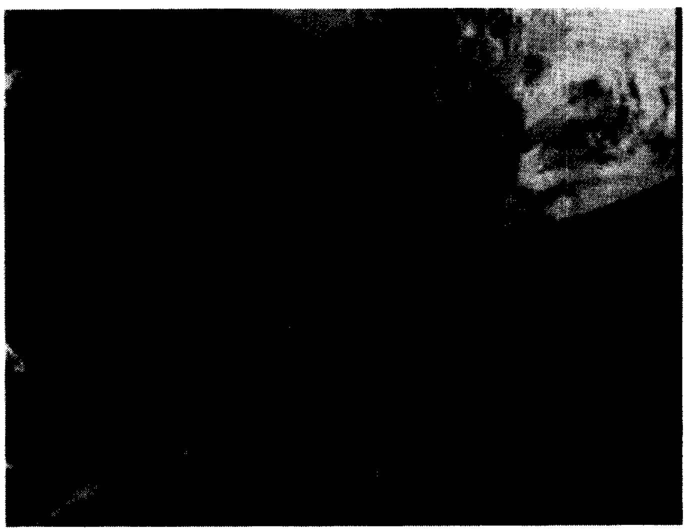

FIG.: 1 The actual imaged pictures on the orbit

4. ONBOARD PROCESSING OF VIBRATIONAL DATA

For the purpose of detecting unusual events (for example, an unexpected collision) and others, the effectiveness of the onboard signal processing, such as Wavelet analysis and STFT (Short Time Fourier Transform). If unusual events can be detected automatically, the method can be embedded into the onboard processing unit as the onboard supervisor. The FFT can find out the frequency information of the signal but it cannot detect the specific time it occurred. On the other hand, the STFT and Wavelet analysis can detect the frequency information and the event time simultaneously. The STFT maps a signal into a two-dimensional function of time and frequency at equal intervals (Fig.2). Wavelet analysis allows the use of long time intervals where more precise low frequency information can be extracted, and shorter regions where high frequency information can be extracted (Fig.3). The vertical axis represents frequency and the horizontal axis represents time in both figures.

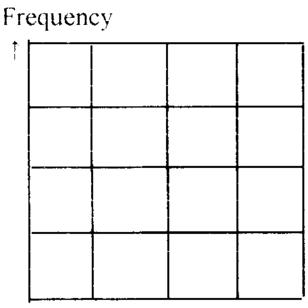

FIG.:2 STFT

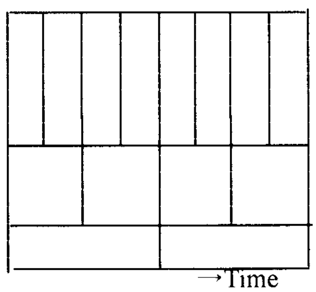

FIG.:3 Wavelet Analysis

The validity of these signal analysis techniques was tested with the 2-dimensional model of the multi-manipulator system [1] with 4-DOF (Degrees Of Freedom) arm (Fig.4). Accelerometers were fitted at the tip of the arm's 1-joint and received the signal in the PC with 4096Hz sampling frequency. The arm was manipulated by joysticks with about 10mm/sec speed to collide with an object (weighting about 1.0kg). After confirming the signal, the joint's motor was turned active at 1.0sec. Then the arm collided with the object at 2.5sec and collided several times again.

FIG.:4 The configuration of 2-dimensional multi-manipulator system

Fig.5 shows the result of Wavelet analysis (symlet8), Fig.6 shows that of STFT and Fig.7 shows that of FFT. The original signal is displayed at the top of the signal in Fig.5. The bottom signal, d1 has the lower half frequency information of the original. d2 has the lower half of d1, d3 has the lower half of d2, d4 has the lower half of d3, d5 has the lower half of d4 and d6 has the lower half of d5. Since the sampling frequency is 4096Hz, the signal under 256Hz appears in d4 and the signal under 64Hz appears in d6. In the d4 data, a large peak is recognized at 2.5sec (at 1×10^{4th} point of data) and two small peaks at 4.0sec (at 1.6×10^{4th}) and at 4.2sec (at 1.8×10^{4th}). In the d6 data, the small continuous signals can be recognized from 1.0sec (at 0.4×10^{4th}) to 2.7sec (at 1.1×10^{4th}). The peak in d4 represents the arm's collision with the object, and the continuous signal in d6 shows the fact that the joint's motor was active in the duration.

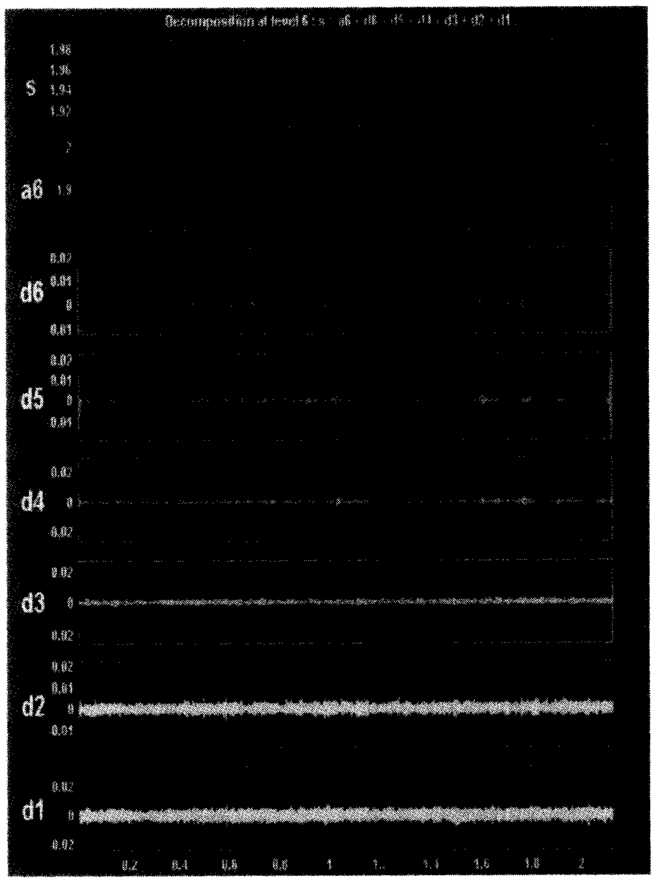

FIG.:5 The result of Wavelet analysis (horizontal axis : the number of data $\times 10^4$)

In the STFT analysis (Fig.6) example, there is a remarkable line at 2.5 seconds with a frequency of 100 ~250Hz, which represents the arm's collision with the object. And also there are two lines at 3.8 and 4.2 seconds, which frequencies distribute up to 250Hz.

These lines represent the arm's collision with the object again. This figure also shows an another event at 1～2.5 seconds with 20～60Hz frequency, showing that the arm's motor was active.

Fig.7 (FFT) shows there are narrow spectrums under 20Hz and 25～65Hz. These are considered to be related to those phenomena described above, but do not show any information in time domain.

Eventually the validity of STFT and Wavelet processing of vibration data was confirmed to detect the frequency and the time on which the arm's collision occured and the arm's motor was active / inactive.

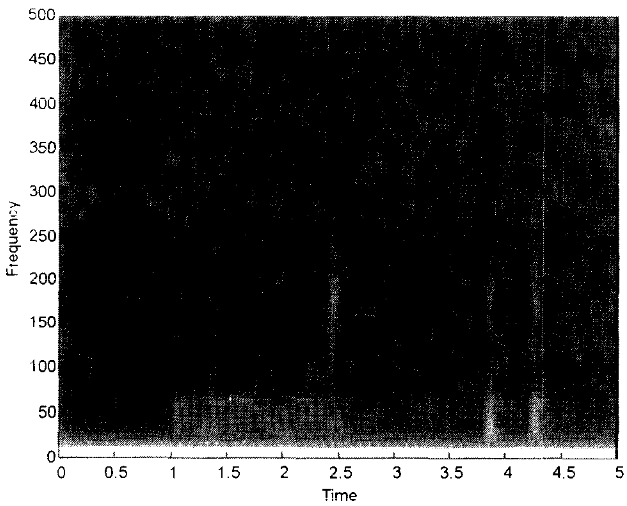

FIG.:6 STFT analysis

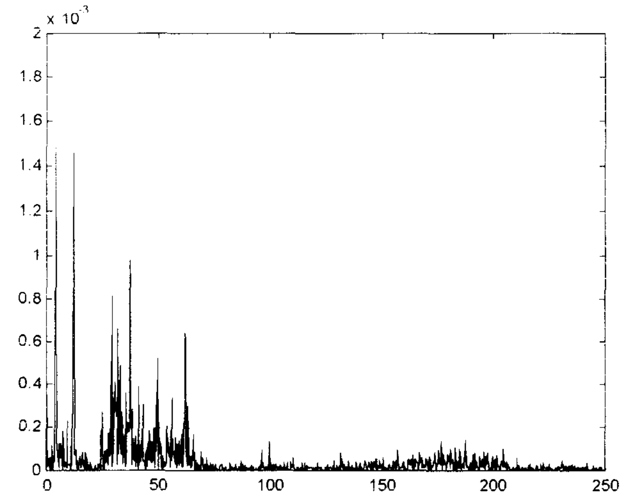

FIG.:7 FFT analysis

Further offline analysis is executed in our experiment to study the possibility of the onboard perception by signal processing.

We measured the processing time of these data on the PC. The processing speed of the microprocessor is 300MHz (with DSP) and the Operating System is WindowsNT4.0. Table.1 shows the processing time of Wavelet analysis. Each processing time was within 0.3sec. Table.2 shows the processing time of STFT. Each processing time was within 0.2sec

TABLE.:1 The processing time of Wavelet (sec.)

	Haar	Daubechies6	Symlets8
Level 3	0.13	0.16	0.18
Level 6	0.17	0.22	0.23
Level 9	0.21	0.26	0.27

TABLE.:2 The processing time of STFT (sec.)

Window length / Overlapped	64	128	256
Half	0.19	0.19	0.18

From the above results, 300MHz microprocessor (with DSP) could process 21248 data using Wavelet analysis or STFT within 0.3 seconds. If we can use the onboard perception processor of 30MHz microprocessor (with DSP), over 2000 data would be analyzed in a second. Meantime, the effectiveness of this continuous processing is evaluated further.

5. ONBOARD PROCESSING OF FORCE DATA

Various experiments were executed with ETS-VII (Engineering Test Satellite VII) and still underway. FTS (Force and Torque Sensor) is equipped with the manipulator on ETS-VII and is used for the compliance control, etc. The FTS data was analyzed to evaluate the effectiveness of the onboard measurement and supervision. The FTS data of ETS-VII exist in the 10Hz telemetry format. Fig.8 shows the force data in x-direction when the manipulator grasped the TBTL (TaskBoard TooLhead) and Fig.9 shows the torque data respectively. Various phenomena were recognized from these data.

Time	Events
1) 0--300	change of arm's activation of the motor
2) 346-> 3)	tool contact TBTL and trace on it
3) 460	finish tracing
4) 460-660	the arm control with x-directional force 20N
5) 617	latch of tool finger
6) 662	change of operation
7) 688	change of compliance mode
8) 740-800	**torque of tool torquer**
9) 795	latch of tool torquer
10) 880	change of motion (stop->move)

(from torque data)

- 617 latch of tool finger
- 662 change of operation
- 688 change of compliance mode
- 740-800 torque of tool torquer

Fig.8 shows the manipulator moved to x-direction 1mm/sec speed from 350 to 460sec and was controlled with x-directional force of 20N from 460 to 660sec for the grasping operation. The force increases lineally up to 24N at 460sec by the term of viscosity, equal to 3.75N. There are peaks at every 40 seconds from 460 to 660sec by the reset function of friction compensator. Fig.10 shows the x-directional data of the similar experiment on different occasion. These data have similar trends with respect to each action, such as the tool's contact to TBTL, the tool's trace on it, the tool finger's latch/unlatch, the change of manipulator's activation of the motor and the change of compliance mode etc. This analysis sugests that the FTS data changes nominally in particular pattern, which precisely reflects the context of robot action. Fig.11 shows the result of the wavelet analysis in certain frequency areas. The peak at 500sec (5000thdata) represents that the tool captured TBTL, and another peak at 700sec (7000thdata) represents the change of the arm's control mode.

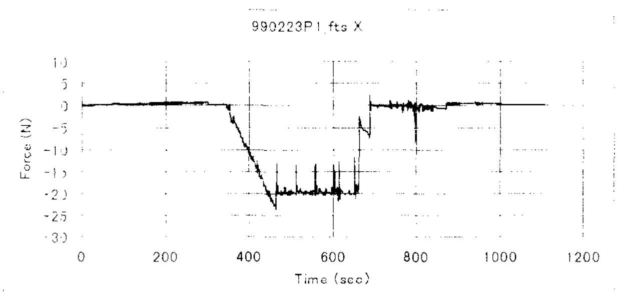

FIG.: 8 the force data of x-direction

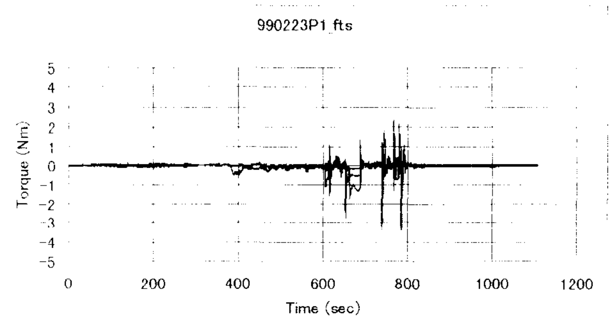

FIG.: 9 the torque data

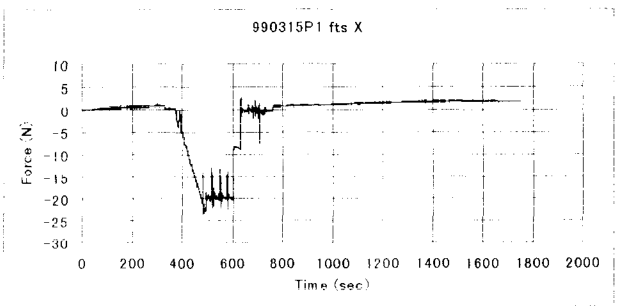

FIG.: 10 force data of x-direciton of another day

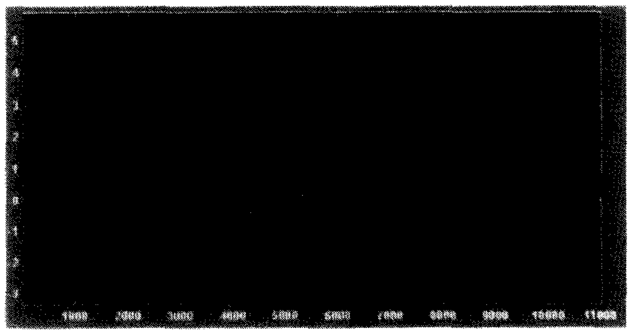

FIG.: 11 the result of the Wavelet analysis (sec.)

The FTS data from the target satellite berthing experiments was also analyzed. Fig.12 and Fig.13 show the forces and torques data of the experiments. In this experiment, at first the manipulator grasped the target satellite, then the docking mechanism(DM) was opened and finally the target satellite was separated from the chaser satellite. The target satellite was manipulated 600mm and next it moved to the original position and the DM was latched. The followings are the observed events from Fig.12 and Fig.13.

Time	Events
1) 280-420	opening of the DM
2) 700-1250	joint activation and arm's vibration
3) 1130-1180	arm's vibration
4) 1750-1900	closing of the DM

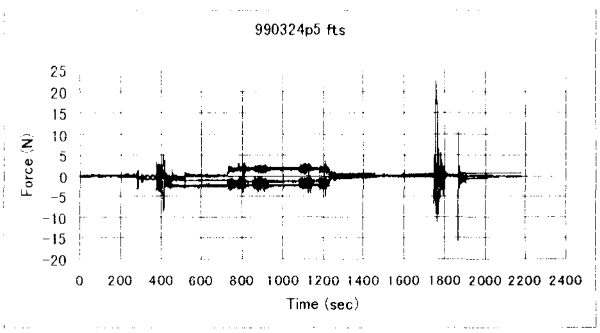

FIG.: 12 Forces data of the target berthing experiment

Fig.14 shows the expanded portion of Fig.12 (from 1100 to 1200sec). The result shows the arm's vibration after joint activation was finished (from 1140 to 1180sec). The vibration is about 0.11Hz which matches the result from the computer simulation.

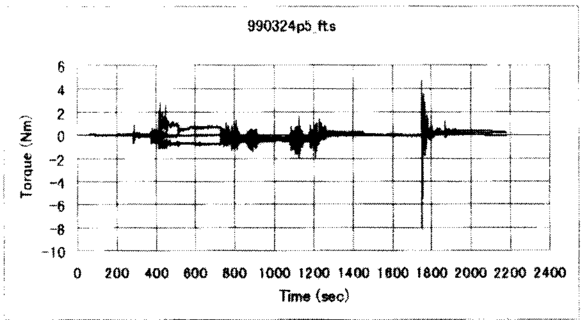

FIG.:13 Torque data of the target berthing experiment

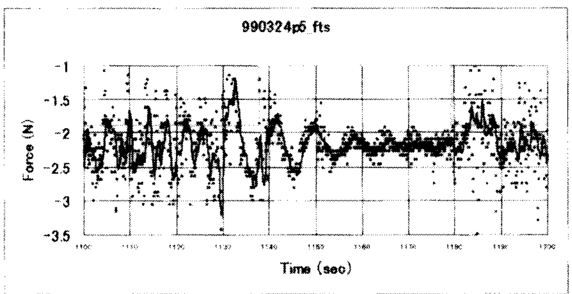

FIG.:14 Expanded figure of Fig.12 (1100sec∼1200sec)

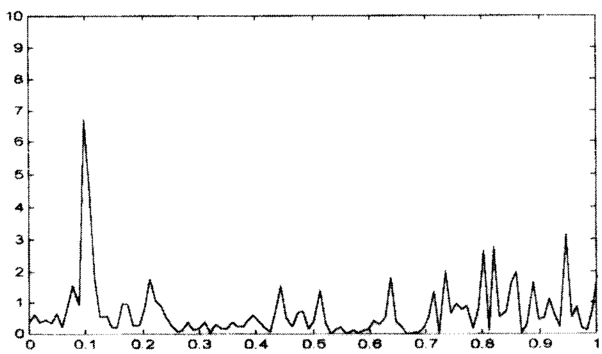

FIG.: 15 FFT analysis on the data of Fig.14 (1100sec∼1200sec)

Fig.15 shows FFT analysis on the data of Fig.14. There is the largest peak nearly 0.11Hz which is the frequency of the arm's vibration. Fig.17 shows the wavelet analysis of the force data of the x-direction which is shown in Fig.12. The same data is shown in Fig.16 for comparison. In Fig.17, as white is brighter, the frequency signal becomes stronger. As the position is upper, the component of the frequency becomes lower. There are the low frequency signal at near 400 and 1800 seconds. These signals reflect the DM latching and unlatching. This analysis suggests that the FTS data is also effective for the detection of the vibrational characterizations.

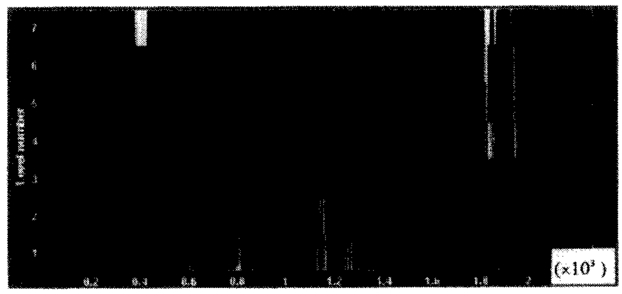

FIG.:17 Result of Wavelet analysis

6. CONCLUSIONS AND ACKNOWLEDGEMENTS

The study confirmed the middlewared JPEG is effective for onboard visual processing, and signal processing with Wavelet analysis and STFT is effective to detect the unusual collision. And the study also recognized the acoustic vibration and force data are effective for the detection of the nominal status, such as event and status, as well as for the detection of the vibrational characterizations.

Onboard perception processing is expected in future space robots, and some applications and laboratory analysis are introduced in this paper. We would like to recognize various supports from members of the related projects.

REFERENCES

[1] Y.OHKAMI et al. "Research and Development of Reconfigurable Brachiating Space Robots", 8TH i-SAIRAS, 1999

[2] K.Ozawa et al. "On-board monitor camera for COMETS", 42ND Space Sciences and Technology Conference of Japan, 1998

[3] T.KASAI et al. "Results of the ETS-7 Mission– Rendezvous Docking and Space Robotics Experiments", 8TH i-SAIRAS, 1999

[4] Y.WAKABAYASHI, et al, "A Design of Lunar Rovers for High Work Performance", 8TH i-SAIRAS , 1999