STEREO VISION MEASUREMENT SYSTEM QUALIFICATION AND PRELIMINARY PERFORMANCE TEST RESULTS

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ABSTRACT

The paper presents the Stereo Vision Measurement System. The system has been developed at proto-flight model level and features the stereo vision processing for in space measurement of the environment geometry.
The SVMS subsystems and the relevant qualification tests are presented.
Preliminary evaluations of the performances of the software system by using the laboratory prototype are included.

1. INTRODUCTION

Following two demonstration phases carried out on behalf of both ASI and ESA, Tecnomare is now completing a development project on behalf of the Italian Space Agency for a flight prototype of a Vision System for space application based on Stereo and Mono computer vision. The system allows for real time measurement of position and attitude and contemporary tracking of objects based on either stereo or single view computer vision.
The SVMS main functions are implemented taking into account tasks such as geometric measurements, geometric modeling, satellite rendez-vous and docking, etc.
The performance data (with TVcameras baseline of 180 mm and lens field of view of 40°) are: pose measurement accuracy stereo view 5.9 mm @ 1 m rms (position) and 0.59 deg @ 1 m rms (attitude); pose measurement accuracy single view 15 mm @ 1 m rms (position) and 3 deg @ 1 m rms (attitude). The Tracking rate is 2 Hz and the Point Measurement rate is 10 Hz.
The Flight Electronics, compliant with Low Earth Orbit external environment requirements, is based on:

- Frame Grabber fitted with CPU boards and VME rack manufactured by Aitech for space applications
- Pan and Tilt Controller boards developed and space qualified by Galileo Avionica.

The development of the system includes the following critical aspects:

- Design and production of space qualified SW based on modular architecture and library of specific Computer Vision tasks (single view measurement, stereovision measurement, multiple points measurement, multiple point tracking, object tracking, geometric modeling based on primitive manifolds)
- Space qualification (T/V, TID and SEE tests) of TV cameras ruggedized by Tecnomare.

The paper includes in particular:

- the presentation of the TVcamera subsystem based on ruggedization by Tecnomare of Sony COTS components and the description of the qualification campaign for Low Earth Orbit (taking into account the thermo-vacuum environment, causing possible components failure due to high vacuum levels as well as overheating of the camera due to the lack of convection cooling; the radiation environment, causing components failure due to irradiation of γ-rays or bulk damage and Single Event Effects (SEE) due to heavy ions and protons);
- the presentation of the Pan and Tilt Controller boards, including the design and results of the preliminary functional tests before the qualification tests
- the results of the software system tests with the Prototype, focusing on the performance of the vision system as regard the measurement of position and attitude and contemporary tracking of objects.

The paper conclusion will include an overview of the possible application of the Vision System, including robotic operation assistance, planetary vehicle navigation and space vehicle maneuvering.

2. SVMS GENERAL DESCRIPTION

The SVMS has been designed as a generic purpose computer vision based sensor for LEO applications. As such, it is capable of performing monitoring, visual inspection and real time measurement of position and attitude of objects, as well as real time tracking of moving objects. Performance data, with a cameras

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baseline of 180 mm and lenses field of view of 40° are detailed in Table 1.

Pose measurement accuracy RMS at 1 m		
stereo view	(position)	5.9 mm
	(attitude)	0.59 deg
single view	(position)	15 mm
	(attitude)	3 deg
Tracking rate		2 Hz
Point Measurement rate		10 Hz

Table 1 - SVMS General Performances

SVMS is a complete vision system, implementing many different features. Its main functions are:

- measurement of 3D Euclidean coordinates, distance between two points, planar areas
- tracking of up to 6 points that can be contemporarily measured
- tracking of a target object by using its geometric model
- depth map reconstruction of the imaged scene
- fitting to extracted 3D data of different primitives (cylinder, plane and straight line).

A laboratory prototype (Fig. 1) has been used to develop and test the different software modules.

Fig. 1 - SVMS Laboratory Prototype

The SVMS is composed of two main parts:

- The Flight Segment (FS), including all the flight hardware and software
- The Ground Segment (GS), acting as interface for the remote Operator who issues macro commands through the Ground Man Machine Interface. An auxiliary Man Machine Interface has been developed to allow astronauts to command the system directly on orbit.

The Flight Segment (see Fig. 2) is composed of:

- **Imaging Unit** (IU): two analogue black & white cameras and the mechanical structure supporting them, its main issue is to maintain the necessary mechanical stability of the cameras baseline over the range of different environmental conditions (flight vibrations and shocks, day/night cycles, orbit parameters etc.)
- **Illuminator**: four lamps to provide the capability to light objects at short distance (1 – 1.5 m)
- **Pan and Tilt** (P&T): two degrees of freedom gimbal to re-orient cameras and lamps
- **Flight Electronics** (FE): algorithmic computation is performed on flight by the FE, which acquires and elaborates camera images, performs measurements and tracking, handles the communications with the SVMS GS, controls the P&T
- **Flight Software**: software development is based on the RealTime extension of the Unified Modeling Language. This approach grants many advantages, among with: easier production of re-usable software modules, easy portability to different environments, simple test and debugging, quickness in documentation generation, etc. The communication between FS and GS is a key issue for the system behaviour. Two channels have been implemented:
    - The uplink channel (GS to FS) used to transmit macro instructions to the FS and for SW or data upload; it is based on the reliable MIL-STD-1553 protocol
    - The downlink channel (FS to GS), based on MPEG transport stream, which presents two different elementary streams: a video stream with the compressed images and a metadata stream with the information on the global FS state, including the measurement data.

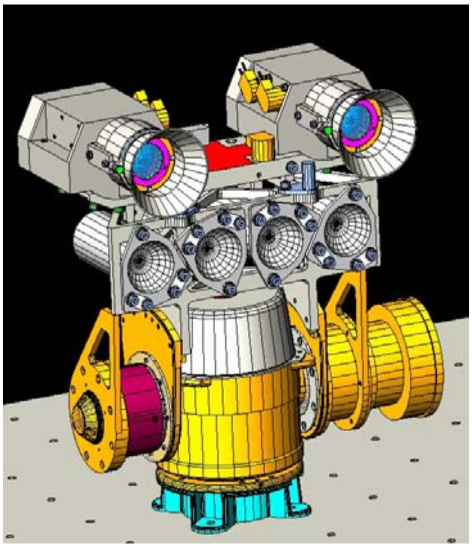

Fig. 2 - SVMS ProtoFlight Model

While maintaining the required flexibility to various mission applications, the International Space Station (ISS) external scientific payloads application has been considered as baseline mission for the detail design. In this scenario, the FS is installed on an Express Pallet Adapter (ExPA) and is commanded from Earth through the GS.

3. IMAGING UNIT

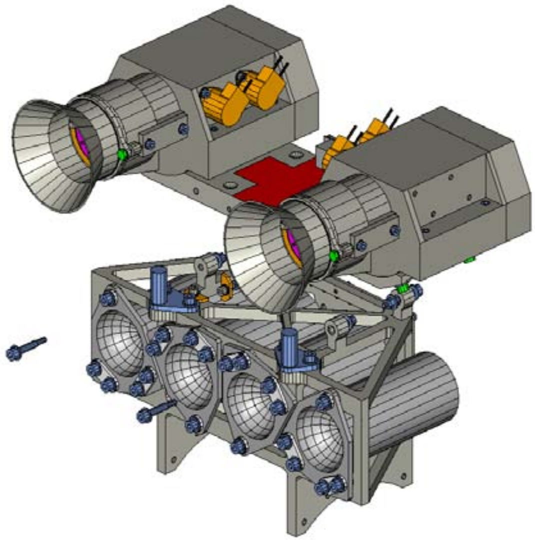

Fig. 3 - Imaging Unit

The Imaging Unit (see Fig. 3) features the following characteristics:

- Active thermal control to maintain a stable temperature in measuring conditions
- Symmetrical and simple design
- Use of high conductivity materials to minimize thermal gradients
- Annealed structural parts to avoid distortions due to internal stress relaxation.

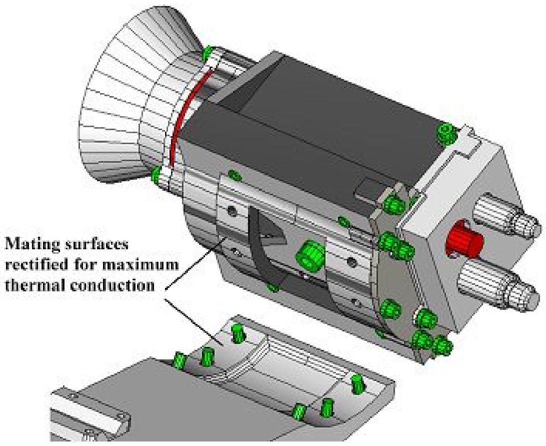

Fig. 4 – Camera case

The camera cases (see Fig. 4) have been produced with the:

- Optical axis alignment guaranteed by a conical coupling between lens and camera case
- shielding of the camera from radiation with an aluminum wall 3 mm thick (as a minimum) in each direction.

4.1 Imaging Unit Cameras

On the basis of the program policy of the SVMS project, Tecnomare has evaluated and tested different COTS cameras to be used for the Imaging Unit. In the end, trade-off studies indicated SONY XC-ST70CE as the best suitable camera for this application. The choice has been driven both by mechanical constraints (size and mass, vibrations and shock resistance, temperature ranges) and by optical constraints (Charged Coupled Devices (CCD) size and resolution, sensitivity, shutter control). Tecnomare endeavoured the space ruggedization and qualification of some of these units for the protoflight model of the SVMS.

The cameras had to be ruggedized and then tested to qualification levels for protoflight hardware. This included several issues to be verified and dealt with such as:

- **Thermovacuum Analysis and Qualification**: thermovacuum stability of materials and electronic components, as well as the operative temperature range of the camera in vacuum conditions, because of the lack of the cooling effect of natural air convection.
- **Radiation Analysis and Qualification**: radiation tolerance to γ-rays and to trapped protons and heavy ions up to LEO levels referred to mission duration.

To guarantee the correct working of the camera, the effects of the thermovacuum and radiation environments on the camera MTBF have been tested and analyzed. This led to the necessity of a ruggedization adding a conduction cooling aluminum heat sink and a shielding of 3mm aluminum, 0.5mm tungsten and 2.5mm of polyethylene for both ionizing radiations and trapped particles. Tests and analyses conducted on the modified camera proved that:

- the camera can withstand a full thermovacuum qualification test for protoflight hardware without any alteration in performances with an heat sink having a thermal resistance of 46 K/W or less.
- camera spoilage after a TID of 30 Gy is negligible. No blemished pixels are present, the diminution in mean grey level of the images acquired during the test imputable to camera spoilage is 1.1%.
- permanent blemished pixels due to protons cumulated fluence corresponding to 1 year in LEO

of the unshielded camera are less than 0.003 % of the CCD surface and thus negligible.

- temporary blemished pixels due to the same fluence of the camera shielded with 3 mm of aluminum, 0.5 mm of tungsten and 2.5mm of polyethylene are less than 0.003 % of the CCD surface and thus negligible.

4. PAN & TILT UNIT

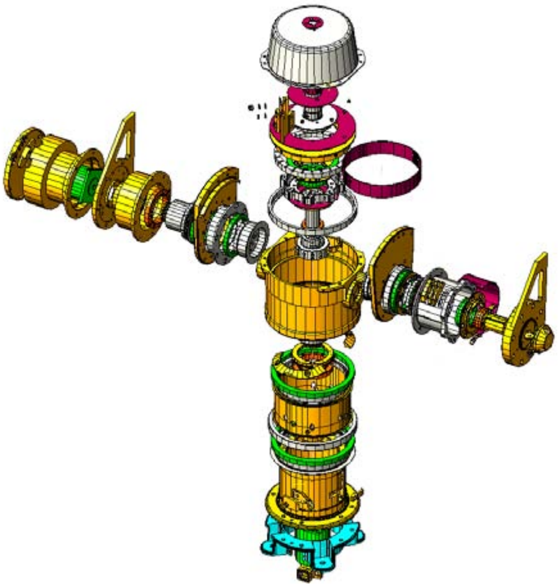

Fig. 5 – Pan & Tilt Unit

The Pan & Tilt Unit (Fig. 5), based on space qualified components for robotic actuator, has been design optimizing the harness routing and the structural and thermal aspects.

Cable paths have been carefully designed in order to respect minimum bending radius of the wires, to minimize cable stress during P&T operations, to minimize impact on P&T working range and to protect cables from wearing damage. Resolver cable shields are connected to P&T frames in order to perform signal bonding.

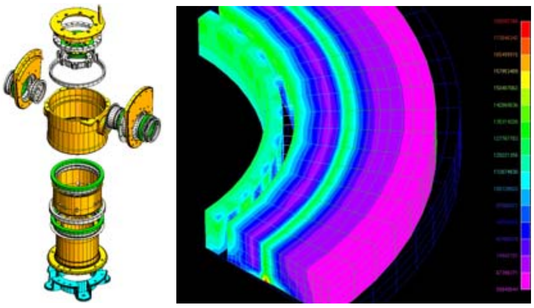

Fig. 6 – Pan & Tilt Unit Bearings

The bearing application aspects was deeply investigated.

Kaydon slim bearings have been selected. Differential thermal expansions between bearings inner and outer housings have been evaluated. Under extreme thermal variations, the different coefficients of thermal expansion of steel bearings and aluminum housings can lead to high stresses or loss of contact between the bearing and the housings. A FEM analysis has been performed to assess the problem: it has been decided to strengthen the ball bearings on their inner and outer diameters with thin steel rings.

4.2 Safety Latching Device

Safety Latching Device has been developed in order to allow for safe launch and re-entry of the SVMS (in launch configuration, see Fig. 7).

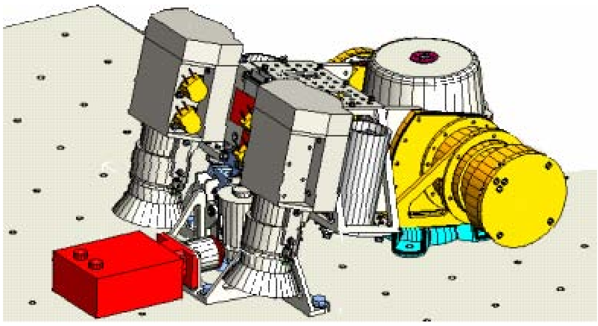

Fig. 7 – SVMS in launch configuration

Lightness, compactness and reliability are the main design guidelines. Latching Device frame (see Fig. 8) has been designed in order to ensure maximum stiffness and minimum encumbrance. Bevel gears reduce height and brass bushes are used to reduce friction between pins and moving elements.

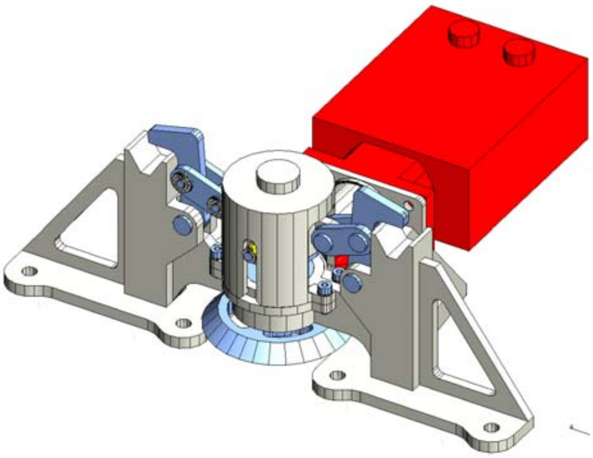

Fig. 8 – Safety Latching Device

5. FLIGHT ELECTRONICS

The Flight Electronics (see Fig. 9) is based on:

- 3 Aitech Systems VME boards (2 stereo pair frame grabbers and 1 video compressor), including communication interfaces (MIL-STD-1553 and Ethernet 10/100)
- 2 VME boards for P&T management designed and manufactured by Galileo Avionica in the frame of the SVMS contract (Pan & Tilt HW Controller)

Fig. 9 – SVMS Flight Electronics

5.1 Pan & Tilt HW Controller

The Pan and Tilt Controller Subsystem is in charge of controlling the Pan and Tilt motors of the SVMS camera, according to the information received by the Central Processor Board, trough VME Bus. Moreover it manages the opening and closing operation of the Pan and Tilt latching device.

The Pan and Tilt Controller Subsystem includes all the redundancies required to guarantee the Pan and Tilt motion (for stowing) even in case of a single failure.

The Subsystem is composed of the following three main parts:

- Motor Driver – Resolver Acquisition Board (MD-RAB);
- Switch Block – Emergency Control Unit (SB-ECU);
- Nominal and Contingency power Supplies.

The Motor Driver-Resolver Acquisition Board is composed of the circuitry to perform the following main functions:

- to provide the reference signals to Pan Coarse and Fine output resolvers and Tilt Coarse and Fine output resolvers;
- to acquire signals coming from the four resolvers (angular positions) and to convert them into digital data with a 16 bits resolution (Resolver Acquisition function);
- to provide a VME I/O bus slave interface to access the board functionality for communication, data transfer purposes, L/D command/status, Illuminator command;
- to receive the digital commands via VME bus from the high power processor board;
- to transmit the digital data via VME bus to the high power processor board;
- to drive the Pan stepper motor through a dedicated two phases bridge, in half step mode current shaping, to allow position tracking and control;
- to drive the Tilt stepper motor through a dedicated two phases bridge, in half step mode current shaping, to allow position tracking and control;
- to interface the SB through dedicated digital lines to manage the latching and delatching operations;
- to acquire the Latching Device status through dedicated lines;

to manage the Illuminator power line.

The Switch Block – Emergency Control Board is composed by:

- Switch Block (SB)
- Emergency Control Unit (ECU).

The two parts of the board, SB and ECU, are galvanically insulated and no data or power exchange between them is foreseen.

The SB-ECU assembly occupies one VME slot (double height).

The Switch Block – Emergency Control Unit connection lines (connections with the power supply lines, VME bus standard signals, emergency controls, +12V power line and +28V power line) are routed through P1 and P2 VME rear connectors.

The SB and the ECU parts are each other galvanically insulated with a isolation voltage ≥ 0.5 kVdc.

The Switch Block is in charge of providing the following set of functionality:

- to switch on/off the illuminator lamp;
- to perform the latching device opening/closing operations, provided with overcurrent protection;
- to provide polarisation and acquisition circuitry for Stowage and LD closed status.

All the operations are performed according to the command received by the digital lines coming from the MD-RAB. The Switch Board is active only in Nominal Mode. P1 connector is used only for VME supply and not for VME signals, P2 connector for all the other lines.

The Emergency Control Unit module manages the contingency situations which might occur during Pan and Tilt HW controller operating in nominal mode.

The main task to be performed by the Emergency Control Unit consists of reaching a known resting position in order to preserve the mechanical system functionality by executing an autonomous fixed sequence of operations. Such a sequence of emergency actions is activated upon external trigger on the Emergency_Cmd_Start discrete digital input line and the status of the action in progress can be monitored by reading the level of Emergency_Cmd_Stat_1 and Emergency_Cmd_Stat_2 discrete digital output lines. The coding of Emergency_Cmd_Stat_1 and Emergency_Cmd_Stat_2 lines is described in the follow.

To allow execution of emergency actions the main functionalities of the Emergency Control Unit are:

- to directly interface the spacecraft through dedicated line, providing information about recovery action status;
- to generate the phase signals for the Pan and Tilt motor drivers, according to hardware-coded settings (direction, velocity and current level) and to control the current level of the power bridges;
- to manage the latching device closing operation;
- to acquire the Stowage and LD closed status and the Pan and Tilt End switches.

The above listed functions are performed in a fixed sequence; they are hard-coded into the Contingency FPGA module and can be summarised as:

1. At power-up, the FPGA sets the output word to “10” for about 3,5 seconds;
2. After that, the FPGA checks if system axis are unlocked. This operation goes on for about 3,5 seconds. During this time the FPGA sets the output word to “01”. If the axis are locked, all the following operations are not performed and the FPGA sets the output word to “11”;
3. the FPGA sets the output word to “10” and waits for the Start Command;
4. when the start command is received, the FPGA enables the conditioning of the Pan and Tilt End switches;
5. the FPGA drives the Pan motor in full-step mode in the pre-set direction (with pre-set velocity and motor current) until the Pan End switch changes its status or an internal watch-dog breaks the operation after about 16’ (in this case all the following operations are not performed and the FPGA sets the output word to “00”);
6. drives the Tilt motor in full-step mode in the pre-set direction (with pre-set velocity and motor current) until the Tilt End switch changes its status or an internal watch-dog breaks the operation after about 9’ (in this case all the following operations are not performed and the FPGA sets the output word to “00”);
7. removes the conditioning of Pan and Tilt End switches;
8. drives the LD motor in the closing direction for about 5’;
9. enables the conditioning of the Stowage and LD closed contacts;
10. acquires the Stowage and LD closed status;
11. removes the conditioning of Stowage and LD closed contacts;
12. sets the output word to “00” if at least one of the Stowage or LD_closed Contatcts is open or to “11” if both the contacts are close.

A two bits word is provided to the spacecraft by the FPGA through dedicated lines to inform about the recovery status situation. This word is coded as follow:

Bit 1	Bit 0	Status
0	0	a) ECU off b) Bad conclusion of contingency sequence
0	1	a) Performing recovery sequence b) Performing initial checking
1	0	a) Performing board warm-up b) ECU waiting for contingency starting command, provided that during the axes status checking the axes result un-locked
1	1	a) System axes locked at start-up b) System axes locked at the end of the Contingency sequence.

The contingency sequence is aborted when the internal watch-dog breaks the operation. In this case there is a bad conclusion of the contingency sequence.

6. SOFTWARE SYSTEM TEST

The system functions have been preliminary tested using the laboratory prototype (see Fig. 10):

- measurement of 3D Euclidean coordinates, distance between two points, planar areas
- tracking of up to 6 points that can be contemporarily measured
- tracking of a target object by using its geometric model and contemporarily measurement of its position and orientation
- depth map reconstruction of the imaged scene
- fitting to extracted 3D data of different primitives (cylinder, plane and straight line).

Fig. 10 – Laboratory Test Setup

The performance results are compliant with the Flight Model expected results.

The verifications highlighted the possibilities relevant to the innovative tracking of non-cooperative object based on their geometric model. The system is able to track the moving object commanding the P&T Unit motion and contemporary measure the position and orientation of the object with the previously declared accuracy.

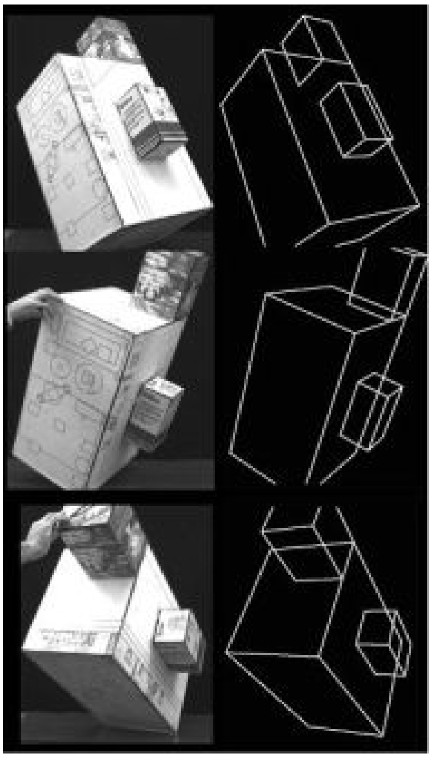

Fig. 11 – SVMS Model Based Tracking

In Fig. 11 the object is moved in the space and the wire-line view of the object presents the updated measurement of the position and orientation.
As shown in Fig. 12 the tracking and measurement of the object is maintained also with partial occlusion of the scene or the temporary occlusion of the scene to one camera.

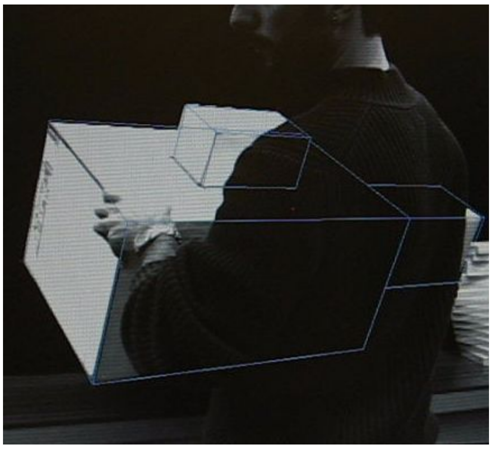

Fig. 12 – SVMS Model Based Tracking with partial occlusion of the scene

The performances have been verified also for the measurement of the points of the scene. In Fig. 13 the measurement of the depth of points in the scene is presented using the rainbow approach.

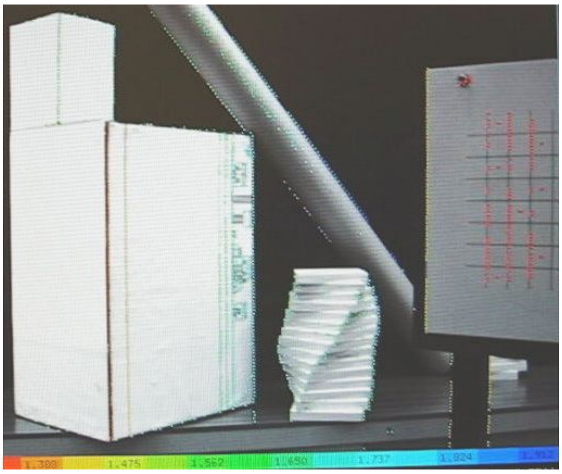

Fig. 13 – SVMS Depth Map of the scene