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Efficient Embedded Hardware Architecture for Stabilised Tracking Sighting System of Armoured Fighting Vehicles

Kamlesh Verma[#,@,*], Debashis Ghosh[@], Rajeev Marathe[#], and Avnish Kumar[#]

[#]DRDO-Instruments Research and Development Establishment, Dehradun - 248 008, India
[@]Department of Electronics and Communication Engineering, Indian Institute of Technology Roorkee - 247 667, India
[*]E-mail: kamlesh@irde.drdo.in

ABSTRACT

A line-of-sight stabilised sighting system, capable of target tracking and video stabilisation is a prime requirement of any armoured fighting tank vehicle for military surveillance and weapon firing. Typically, such sighting systems have three prime electro-optical sensors i.e. day camera for viewing in day conditions, thermal camera for night viewing and eye-safe laser range finder for obtaining the target range. For laser guided missile firing, additional laser target designator may be a part of sighting system. This sighting system provides necessary parameters for the fire control computer to compute ballistic offsets to fire conventional ammunition or fire missile. System demands simultaneous interactions with electro-optical sensors, servo sensors, actuators, multi-function display for man-machine interface, fire control computer, logic controller and other sub-systems of tank. Therefore, a complex embedded electronics hardware is needed to respond in real time for such system. An efficient electronics embedded hardware architecture is presented here for the development of this type of sighting system. This hardware has been developed around SHARC 21369 processor and FPGA. A performance evaluation scheme is also presented for this sighting system based on the developed hardware.

Keywords: Hardware architecture; Target detection; Target tracking; Video stabilisation; Visual surveillance

1. INTRODUCTION

In a typical battle field scenario, gunner and commander of the tank carry out the surveillance and acquire target through a sighting system. Generally, sighting systems have three basic electro-optical (EO) sensors i.e. Thermal imager, day TV camera and eye-safe laser range finder (ELRF). Thermal imager works on the principle that every object above zero Kelvin emits heat radiations, which are captured by detector and converted into gray levels to facilitate the distant vision even in pitch dark night conditions. Day camera provides the vision in day light conditions. ELRF is used to find out the range of target. All these sensors are mechanically assembled in a gimbal, mounted on tank platform. Disturbances due to motion, engine vibration and irregular terrain, gets coupled with the gimbal resulting in noisy, blurred, destabilised and unpleasant video. This severely reduces the capability of target recognition, tracking and firing. To counter this blurring, line-of-sight stabilisation is essential. In tank application, gimbals have usually two axes of freedom i.e. azimuth and elevation. A position sensor (resolver or encoder) is used to measure the angular azimuth (Az.) and elevation (El.) position of gimbal. An inertial rate sensor (usually gyro) is placed on the gimbal which senses the disturbance and gives the analog modulated or digital output signal depending upon the gyro selected. This disturbance is processed in an embedded hardware where control laws are implemented in the form of infinite impulse response filters. The compensating error voltage is converted to analog signal using digital to analog converter (DAC) circuitry, which after amplification, drives the servo actuators in the direction opposite to the disturbance movement. Once the gimbal is stabilised, a video tracker card will detect and track the target. This tracker error will be fed to track-controller, to enable the tracking in such a way that target is always kept in the center of the display. For man machine interface, an intelligent multi-function display (MFD) is provided. This gimbal with all related subsystems is named as electro-optical tracking system (EOTS) as shown in Fig. 1.

This paper discusses the important embedded hardware architecture for design and development of target detection and tracking sighting system for visual surveillance with video stabilisation facility due to the implementation of line-of-sight stabilisation technique.

2. RELATED WORK

In depth literature survey is provided in[1-4], where video stabilisation is achieved through only image processing. Kamlesh[5], *et al.* provide a digital video stabilisation with smear removal and real time implementation scheme. A sub-fractional accuracy was achieved through the algorithm. Visual surveillance, target detection and tracking is very well explained in[6-8]. Samet[9], *et al*. have carried out a comparative study of digital PID controller. A motion controller based embedded

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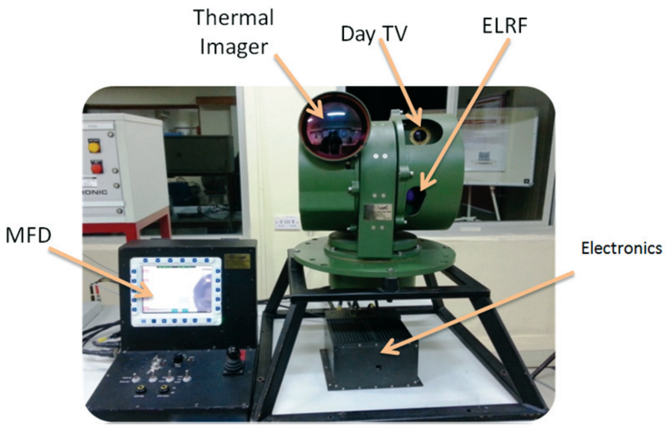

Figure 1. Electro-optical tracking system.

hardware architecture is used to control multi-axis motion controller using servo torquers[10]. A DSP TMS320F28335 was used to implement the controller. Cipriani[11], *et al*. used AMD ATLON XP processor into implement a closed loop controller for a tendon transmission. An embedded architecture was used to implement PID controller for DC torquers with embedded DSP TMS320LF240 in[12] for mobile robots. FPGA was used in[13,16,17,21] where PID controllers were implemented for different applications. An AVR microcontroller was used to implement controller for brushless DC motor in[14], where a double closed loop namely speed and current control loops were realised. A fuzzy, self tuning PID and a feed-forward mechanism was implemented using TMS320C6727 and FPGA. A velocity controlled servo mechanism was realised[18], using IBM AT keypad. A constant velocity was achieved and maintained at the end of motor using tunable PID controller coefficients instead of using FIR or IIR filters. A MOVE processor based servo realisation has been achieved by Tabak[19], where digital filters were represented in the form of polynomials or matrix multiplication and both types were implemented for industrial servo control.

To control advanced force or position by an industrial robot, an open hardware and software architecture was proposed in[20]. Content based analysis for surveillance requirement was proposed by Wei-Kai[22], *et al.* using a system-on-chip solution having content analysis tool and smart camera. This engine also has a dedicated co-processor for doing morphological operations. A TMS320DM642 was utilised for intelligent visual surveillance system capable of detecting and tracking the target of interest[23]. Tracking was achieved using FPGA by Malik[24] by optimising the computational loads and multiplications occurring in the algorithm. A combination of multiple PI and fuzzy control mechanism for a tracking system was developed by Quang[25] using FPGA technology. Tracking algorithms were implemented on XC2v1000 FPGA on Celoxica board[26]. Video stabilisation was achieved in[27] using feature matching architecture. A data reuse algorithm was developed in[28] which provides an efficient hardware architecture for real time video stabilisation. Four independent layers were used to realize the aerial video stabilisation in[29]. FPGA based video stabilisation was proposed by Li[30], where Kalman filter was used effectively. Very good image denoising and quality assessment is provided in[31-41].

3. EMBEDDED HARDWARE DEVELOPMENT

An electro optical tracking system (EOTS) consisting of thermal imager, day TV camera and eye-safe laser range finder has been designed and developed at Instruments Research and Development Establishment lab. The system performance was evaluated in lab and in field, which meets all the required specifications. This system meets all the requirements for integrating in a tank as a surveillance, acquisition and firing sight. An efficient, miniaturised embedded hardware has been designed and developed for EOTS. This hardware differs from classical hardware design approach where two separate electronics boxes are developed, one for control and the other for servo power amplification. Also the novelty lies in optimising SHARC based hardware for simultaneous interfacing of EO sensors, real time compensator output during each 250 µs. period of stabilisation, target tracking and real time interfacing with sub systems like fire control computer. The details of hardware design, development, testing, integration and performance evaluation are presented in following sections.

3.1 Requirement Specifications

The computational load is calculated from the requirement specifications of system. Hardware needs to be interfaced with following:

- RS485 serial link with thermal imager
- RS232 serial link with day camera
- RS232 serial link with ELRF
- RS232 debug port of ADSP21369
- RS422 link for MFD
- RS422 link for Ballistic computer
- RS422 link for logic interface unit
- Synchronous Serial Interface of azimuth encoder
- Synchronous Serial Interface of elevation encoder
- Analog input from azimuth control handle
- Analog input from elevation control handle
- Analog demodulated output of gyro azimuth axis
- Analog demodulated output of gyro elevation axis
- Ethernet link
- CAN port

To meet above requirements, there will be a processor interfaced with Analog to Digital Converter (ADC), Digital to Analog Converter (DAC), Universal Asynchronous Receiver-Transmitter (UART) and TTL digital interfaces. A functional block diagram is as shown in Fig. 3. One Black-Fin BF609 processor of Analog Devices is chosen because it has video processing unit, CAN controller and Ethernet link onchip.

3.2 Embedded Hardware Configuration

The configuration of embedded hardware is as shown in Fig. 2. All servo sensors, actuators, EO sensors and other sub-systems are interfaced as shown in Fig. 2. A motherboard concept with connector PCB at backend is chosen to avoid jumbling of internal wire routing.

3.3 Servo Control Card

A servo control card is designed and developed to meet

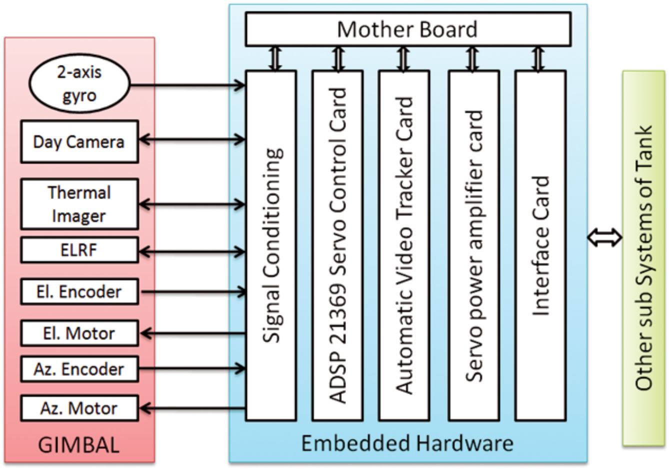

Figure 2. Electronics block diagram.

the real time control requirement. This card is designed around 32 bit floating point, 400 MHz SHARC core, 2 Mbits onchip static random access memory and 6 Mbit of read only memory onchip, which can compute upto 2.4 GFlops at peak performance. ADSP21369 can compute one biquad IIR filter in 5.0 ns, which is desirable as compensators are implemented in the form of IIR filters only. This processor has two separate processing units which comprise of arithmetic logic unit (ALU), multiplier, shifter and data register files.

Combining all these features, this processor provides a very strong solution for servo control of direct drive motors fitted on gimbal for real time servo stabilisation requirements. The main design blocks of this card is detailed in following sections.

3.3.1 Data Acquisition Channel

A very fast data acquisition channel is designed to interface gyro sensor and other analog input signals. Before processing the signals, proper signal conditioning is carried out as shown in Fig. 4. Gyro signals are fed into a differential amplifier for noise removal, followed by low pass filtering to avoid aliasing, then amplified by a gain network; the signal is then selected in multiplexer to be fed to ADC which converts analog signal into digital signal. Now this digital signal is processed in processor. Processor has control laws implemented into it, which gives required error output written on DAC. DAC signal is current amplified in servo power amplifier (SPA), which finally drives the motors to stabilise the gimbal.

The line-of-sight stabilisation accuracy of the system was defined to be ≤ 60 µrad, i.e., 3.4 milli degree. Disturbance of system is sensed by gyro, which has a scale factor of 100 mV/deg/s, so it will give 0.34 mV minimum value corresponding to stabilisation accuracy. The minimum number of bits will therefore be decided by 10 V/2^{15} =0.305 mV, one bit is kept for noise, hence at least 16 bit processing is needed. Therefore a 16 bit data acquisition channel was designed with 1µs fast ADC acquisition time.

3.3.2 Control Laws

The control law scheme implemented in this hardware is described in Fig. 5. There are two basic loops. First loop is stabilisation loop where gyro sensor data acts as a feedback

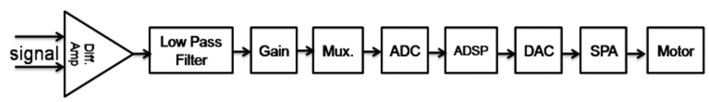

Figure 4. Data acquisition channel.

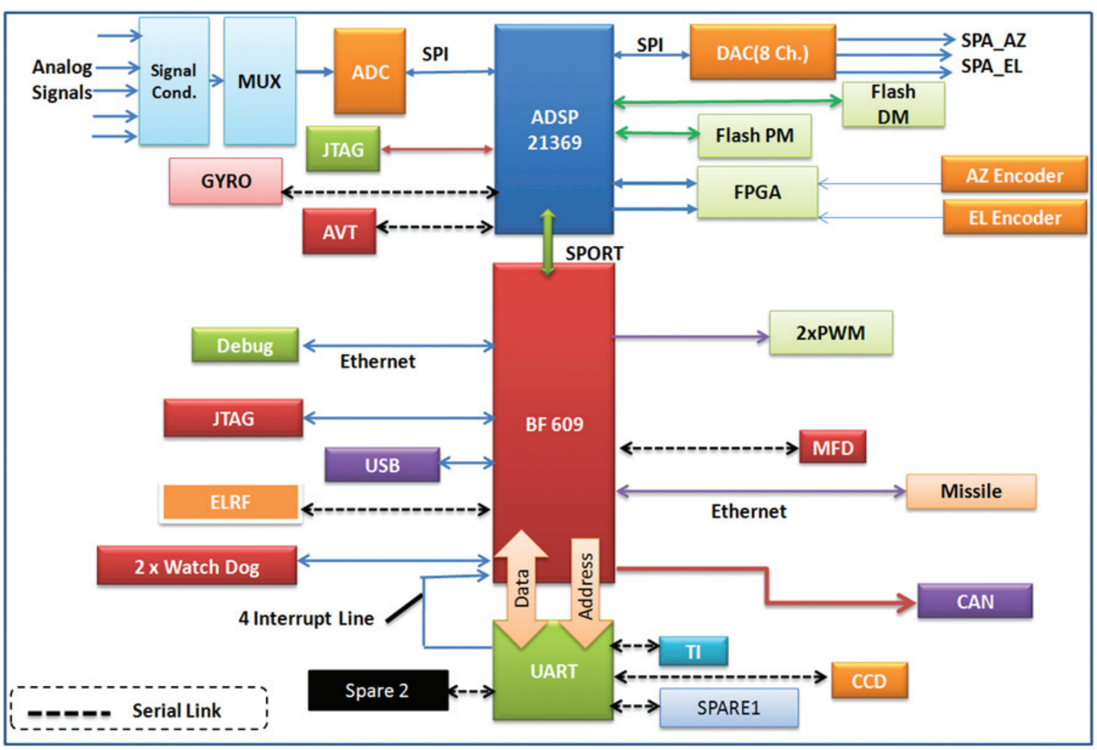

Figure 3. Functional block diagram.

signal and gimbal is inertially stabilised irrespective of the disturbances of host platform.

In stabilisation mode, gimbal follows the commands of control handle/joystick. Second loop is position loop, in which gimbal goes in the specified angular position defined by command signal or follows the host platform positions. In the design stage a mathematical modelling of gimbal including servo sensors, actuators, disturbances etc. is carried out. The frequency response of gimbal is taken and output Bode plot is reshaped to get desired parameters like gain margin ≥6 dB and phase margin in between 30° to 60° etc. A detailed block diagram of controller is as shown in Fig. 5.

3.3.3 Implementation of Control Laws

Control laws in the form of compensators are designed in frequency domain. These compensators are converted into z-domain using bilinear transformation i.e.

$$s = 2/T.((z-1)/(z+1)) \quad (1)$$

where T is sampling time which was taken as 250 µs. This 4kHz frequency is chosen so that the phase lag contributions due to sampling is minimum. Now the main task is to implement these compensators in hardware. Here the role of digital signal processor (DSP) comes in to picture. These types of very fast calculations can be achieved only by using a DSP. The compensators can be implemented using finite impulse response (FIR) or infinite impulse response (IIR) filters. It is to be noted that for the same type of filter specification FIR out-performance in terms of linear phase response, however there will be a very large number (usually in the order of 512, 1024) of coefficients in FIR filter. On the contrary, for the same type of filter specifications, an IIR filter does produce non-linear phase response but involves very less number of coefficients (like 3 for first order and 5 for second order filter). IIR filter implementation is carried out in single order or double order.

A first order IIR equation is given as:

$$y(n)= b_0.x(n) + b_1.x(n-1)- a_1.y(n-1) \quad (2)$$

where b_0 , b_1 and a_1 are the filter coefficients, $x(n)$ is the input data sequence, $y(n)$ is output data sequence and z^{-1} is the delay element, so that $x(n-1)$ is just previous input and $y(n-1)$ is just previous output.

There are two type of processors, integer (16 bit processing) and floating (32 bit processing). To achieve the accuracy and to avoid saturation and accumulation of errors due to residual of calculation, it is always preferable to choose floating point processor. Based upon previous discussions ADSP 21369 processor was chosen. Glue logics are implemented using FPGA.

3.4 Interface Card

Interface card is responsible for interconnecting external sub-systems to the gimbal. This card has necessary UARTs to communicate serially with other subsystems of tank.

3.5 Power Supply Card

All supplies to different cards are generated in this power supply card. Necessary DC-DC converters convert nominal input supply of 28VDC (18-32 VDC full range) to ±5V, ±15V.

3.6 Servo Power Amplifier Card

Servo Power Amplifier (SPA) card provides the required current amplification for the servo motors. Pulse width modulated miniaturised MSK4206 is used. H-bridge and servo power amplifier card is as shown in Fig. 6.

3.7 Automatic Video Tracker Card

Blackfin based Automatic Video Tracker (AVT) card is used for tracking applications. Raw videos from thermal imager and day camera are input to AVT card. Operator brings the tracking window on the target of interest, then as soon as target is inside the window, automatic target tracking function is invoked and gimbal starts following the target. There are three algorithms implemented in AVT for tracking. The selection of these algorithms can be done using the soft buttons programmed in MFD.

3.7.1 Cross Correlation Algorithm

Detecting a tank is a difficult task in desert environment. Tracking of tank is best carried out using cross correlation algorithm in these types of cluttered environment.

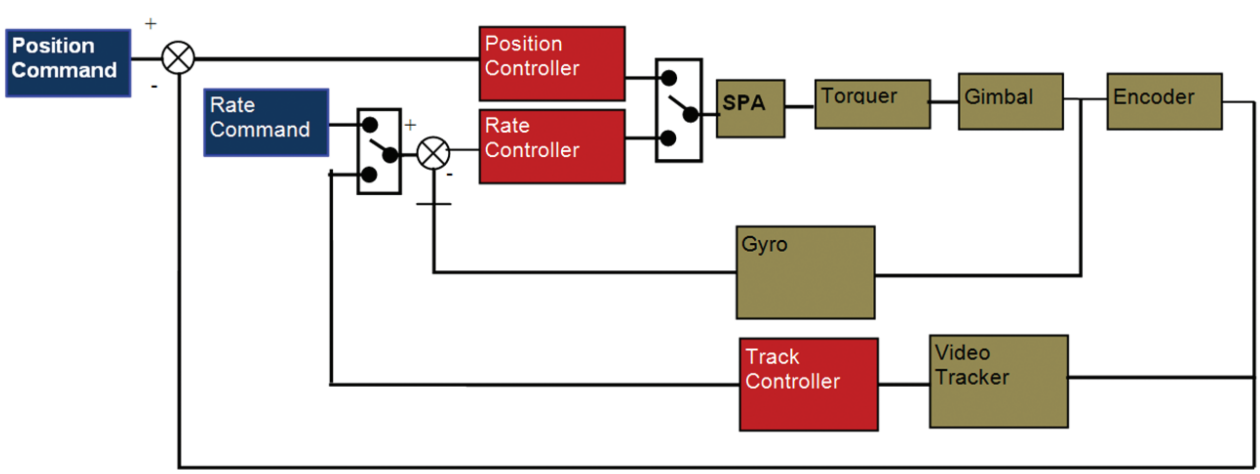

Figure 5. Control block diagram[1].

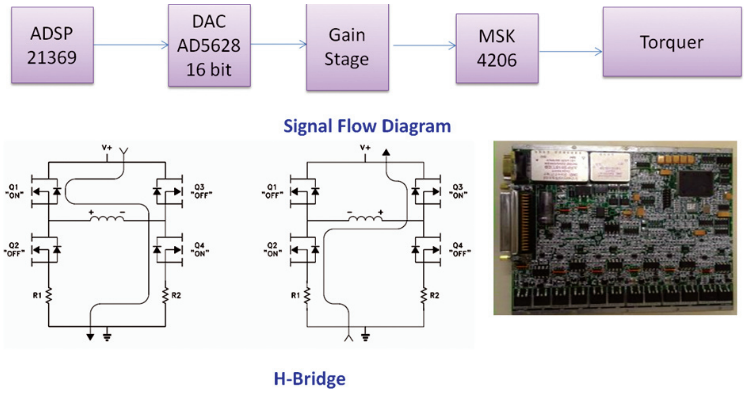

Figure 6. Servo Power Amplifier Card.

3.7.2 *Centroid Algorithm*

When there is a clear background, then centroid algorithm is best suited. This algorithm is ideal for tracking aerial targets.

3.7.3 *Edge Detection Algorithm*

In this algorithm tracking is done by detecting sharp edges of target.

4. MULTI FUNCTION DISPLAY

A ruggedised Multi-Functional Display (MFD) was developed and programmed. This MFD takes three input i.e. raw thermal imager video, raw day camera video and tracked video input. Tank operator can select the desired video. Relevant information will be annotated on video like mode of operation, target range, position of gun and gimbal etc. The MFD as shown in Fig. 1 will have different pages, which are programmed to feed different parameters for different sub-systems.

5. SOFTWARE DEVELOPMENT

The embedded hardware may be real time operating system (RTOS) based or non-RTOS based. The developed hardware is non-RTOS based due to the critical timing requirements. The timings are managed by different timer interrupt subroutines, where the priority of each timer interrupt is well programmed.

In this development main interrupt service routine (ISR) runs on 250 µs. and each serial interrupt frequency is 1 ms. There are three type of software developed. First one is device driver which interacts with the physical layer of hardware integrated circuits is written in 'C' language.

Another software, which is embedded in processor, is application software which contains all the user interactions, sensors interactions, health monitoring, hand shaking signals and other requirements. This software is written in 'C' language. The third software is graphical user interface (GUI) which resides in mission computer for man-machine interface or in personal computer for testing and validation purpose. This software is written in Visual Basic environment. A transition diagram for modes of operation is as shown in Fig. 7 for application software. Through GUI, modes of operations, monitoring and recording of important parameters can be done.

6. COMPUTATIONAL LOAD AND TIMING ANALYSIS

It is always required to have minimum phase delay in control loops. In digital domain design, this phase delay can be minimised by sampling the rate sensor at the highest rate. Gyro rate sensor senses the rate of disturbance. The phase delay is given by following equation:

$$\theta = \omega . T_s/2 \quad (3)$$

where θ is the phase delay, T_s is the sampling time and ω is frequency in radian. Different delay will be observed at different disturbance frequency f as follows

$$\theta = f . T_s . 180° \quad (4)$$

Typically, it is sufficient to sample the servo sensor signals at the rate of 2-4 kilo Hz. It is to be noted that all signal processing must be carried out within this time frame only. Higher the sampling frequency, lesser will be the phase delay. But the cost of lesser phase delay will be, lesser execution time, which demands the fast signal processor. Keeping in view all pros and cons, a very fast ADSP 21369 processor was selected with a sampling period of 4 kilo Hz i.e. 250 µs. A main interrupt sub routine (ISR) is executed at the rate of 4 kHz. There are sixteen data acquisition channels with a fast ADC of acquisition time 1 µs, so total 16 µs will be used to digitise the analog input signals like azimuth and elevation gyro signals with different gains for different slew rates of gimbal. In stabilisation loop, there are total nine single order IIR filters are implemented in which five are for azimuth and four are for elevation channel with different gain management schemes. Stabilisation loop takes a total of 145 µsec. In position loop, a total of ten numbers of single order IIR filters are implemented with different gain management schemes. Other tasks like memory reading, memory writing, updation of different variables, azimuth and elevation torquers current sense monitoring, management of various modes, management of different logic signals took a total time of 24 µs. Therefore total loop execution time of stabilisation loop becomes 16+145+24=185 µs. Similarly the position loop having inputs from encoders executes in similar time frames. The remaining amount of execution time is used as a safety

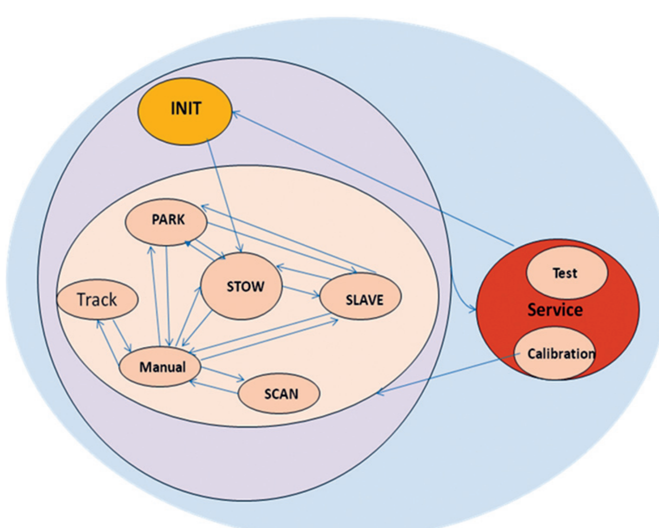

Figure 7. Transition diagram for modes of operation.

margin and futuristic requirements.

Timing can be compared with other similar developed stabilised sighting systems. In two gimbal systems where only two degrees of freedom is required to be controlled in azimuth and elevation axis, 4 kHz sampling is sufficient to control the system. While for four or five gimbal approach where three axis i.e. azimuth, elevation and roll need to be controlled, 4 kHz may not give sufficient time to execute the above tasks, therefore 2 kHz sampling frequency is used in mass stabilised four gimbal design (inner azimuth, inner elevation, outer azimuth and outer elevation) and 1 kHz sampling rate is selected to execute the control tasks in five gimbal (three axis) control scheme.

7. TESTING AND INTEGRATION OF HARDWARE ELECTRONICS WITH GIMBAL

Firstly, independent testing of each card is carried out. This starts from cold testing, where all the major power lines are tested on printed circuit boards (PCB). PCBs are visually inspected for any defect. Then each PCB is powered on independently. For testing of data acquisition channel, sinusoidal signals with varying frequency and amplitude ranges are input to all the channels of multiplexer and output is verified on DAC channels. The output must be free from any distortion. To test the serial RS232/RS422/RS485 channels, a simulated data is sent at different baud rates to the host computer with specified protocol in tell-back mode, where the same data must be received without any distortion in message.

To test the servo power amplifiers, actual load is connected if available, else a resistive-capacitive-inductive load with desired rating is connected and tested for any overdrawing, short-circuiting or heating phenomenon. After testing all cards, full electronics module is integrated over mother-board. Now this whole module is integrated with gimbal and tested for each connectivity. All connectors to be integrated with tank platform were chosen such that they withstand the harsh and rough environment of tank.

8. PERFORMANCE EVALUATION OF EOTS

There are two level of performance evaluation i.e. lab level and field trials.

8.1 Lab Level Testing

The system is thoroughly checked for each parameter. Some of the major parameters are as shown in Table 1. There are three main parameters i.e. stabilisation accuracy, position accuracy and tracking accuracy. To test these parameters, it is not practical to integrate the system on tank, then record the parameters in actual tank running conditions. Therefore a three axis motion simulator machine was used to test stabilisation and position parameters. The EOTS was mounted on this machine. Through a control panel, standard disturbance spectrum is fed to the machine. Then machine induces the tank disturbances into the EOTS and during this time gyro data is recorded for some time. Then this gyro data is post-processed and stabilisation accuracy is determined. The gimbal is maintained at a particular orientation, and after some position command its position is altered. Then again position command is given to make it return to its original position. The difference in these two position is noted several times and the position accuracy is determined. Instead of these electrical methods, optical collimation or laser auto-collimation may also be used to measure stabilisation and position accuracies. Typical stabilisation accuracy plot of azimuth axis measured on three axis motion simulator machine is shown in Fig. 8.

Table 1. Important performance parameter test result

Parameter	Specification	Achieved
Continuous power	≤ 6 Amp	3.1 Amp
	-20° El	-20.07°
Physical freedom	+40° El	+40.06°
	Nx360° Az	Nx360° Az
	Stabilisation	ok
Modes	Position	ok
	Surveillance	±45° az. scan
	Centroid	tracking
Visual tracking	Cross-Correlation	tracking
	Edge Detection	tracking
Stab accuracy	60µrad.	43.07 µrad
Position accuracy	≤ 0.2 mil	0.1 mil
Tracking accuracy	±3 pixels	±3 pixels
Az, slew rate	> 40°/s	55.5°/s
El. slew rate	>20°/s	25.6°/s

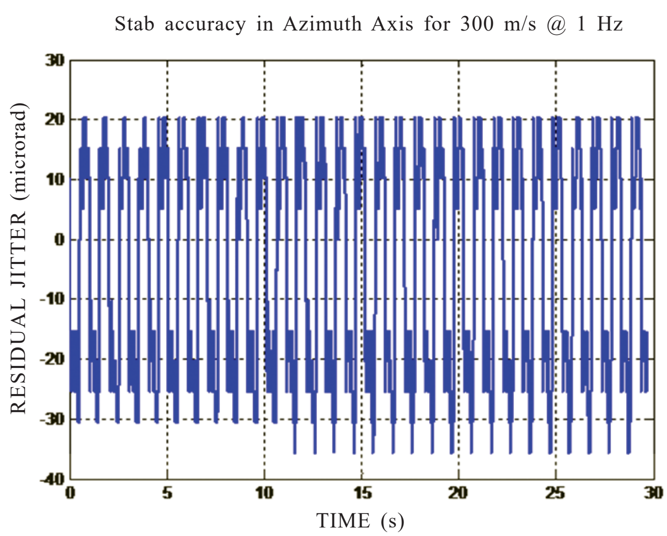

Figure 8. Azimuth stabilisation accuracy.

To measure the accuracy of target tracking, a dynamic target simulator facility is used. This has one hot target for thermal camera and one cold target for day camera tracking. These targets can be moved in a programmed manner i.e. sinusoidal, spiral and random motion etc. with the given rate. The gimbal keeps on following the target and residual errors in pixel is measured.

8.2 Field Trials

The system was field trial evaluated in different field conditions. The gimbal was positioned on a nearby hill and different moving targets like persons, car, jeep and truck etc.

were successfully tracked upto available visible ranges of 1.5 km through day camera as well as through thermal imager. The system was also taken to nearby airforce stations to track the fighter planes. EOTS successfully tracked the aerial targets upto 40 kms due to the hot bright plumes of planes. A sample shot of tracked target at 2 km is as shown in Fig. 9. The designed hardware thus successfully met all the required specifications.

Figure 9. Tracked target with thermal imager

8.3 Performance Results

Some important performance parameters are as placed in Table 1. It can be inferred that the embedded hardware meets all the required parameters for the successful demonstration of EOTS.

9. CONCLUSIONS

An efficient embedded hardware architecture is presented here. This hardware was interfaced and integrated with a electro-optical sighting system which produced excellent performance in terms of stabilisation accuracy, slaving accuracy, target tracking accuracy and video stabilisation for visual surveillance purpose. In future work servo control and interface cards functionality may be embedded in application specific integrated circuit (ASIC) for the further minimisation of hardware.

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CONTRIBUTORS

Mr Kamlesh Verma received BE (ECE) from Madan Mohan Malaviya University of Technology, Gorakhpur, in 2001 and MTech from IIT Kanpur in 2010. Currently he is pursuing PhD from IIT Roorkee. He is serving as a senior Scientist in DRDO-Instruments Research and Development Establishment, Dehradun. His research area of interest is design and development of embedded hardware for line-of-sight stabilisation technology, computer vision, image and video processing.
Contribution in the current study has designed and developed the stabilisation and tracking electronics for EOTS. He has also carried out performance analysis and field trials of EOTS. He is main author of this research work.

Prof. D. Ghosh received BE (Electronics & Communication Engg.) from Malaviya National Inst. of Tech. (erstwhile Malaviya Regional Engg College), Jaipur, in 1993, and MS and PhD in Communication Engg. from IISc Bangalore, in 1996 and 2000, respectively. He is currently Professor & Head in the Dept. of Electronics & Communication Engg., IIT Roorkee. His teaching and research interests include communication systems, signal processing, image/video processing, computer vision, and pattern recognition.
Contribution in the current study he has provided valuable design inputs and supervised the research work in the field of target detection, tracking and video stabilisation.

Mr Rajeev Marathe obtained his BE (ECE) from Madhav Institute of Technology & Science (Jiwaji University), Gwalior, in 1988 and MTech (Electrical Engineering) from IIT Kanpur, in 1997. Presently, he is chief designer of Payload Stabilisation Division in DRDO-Instruments Research and Development Establishment, Dehradun. He has been working in the area of line-of-sight stabilisation and electro-optical fire control systems for land, naval and airborne applications. He bagged the '*DRDO Young Scientist of the Year award'*- 2000 for developing new technologies and devices for defense applications.
Contribution in the current he has designed the controller for realisation of EOTS. He is team leader for the EOTS project.

Mr Avnish Kumar received his BTech (ECE) and MTech (Electronics Engineering) from IIT Roorkee. Currently, he is working Scientist in DRDO-Instruments Research and Development Establishment, Dehradun and is guiding a team of scientists for the design and development of LOS stabilisation, electro-optical surveillance, and fire-control systems for various platforms.
Contribution in the current work: He is Group Director of Servo division and Project Director of EOTS. This EOTS project has been successfully designed and developed under his technical and administrative guidance..