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Design and implementation of a hardware-in-the-loop simulator for a semi-automatic guided missile system

Krešimir Ćosić, Ivica Kopriva *, Todor Kostić, Miroslav Slamić, Marijo Volarević

Institute for Defence Studies, Research and Development, Bijenička 46, 10000 Zagreb, Croatia

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Abstract

Hardware in the loop (HIL) simulation based on modern digital signal processors is a cost-effective technology for the design and evaluation of various sophisticated weapon and industrial systems. In this article a HIL simulation is presented through the very complex problem of modernisation of the semi-automatic command to line of sight (SACLOS) missile system. The presented examples illustrate the importance of the HIL simulation technology for the cost-effective, non-destructive prototype development of such SACLOS systems. The key role of a flexible simulation platform consisting of 4 TMS320C40 digital signal processors for efficient real-time simulation of the implemented SACLOS subsystem models is also emphasised in this paper. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Hardware in the loop simulation; Semi-automatic guided missile system; Digital signal processors; Parallel processing

1. Introduction

Hardware-in-the loop (HIL) simulation has been proven as a cost-effective method in design, development, modification and testing of a various sophisticated weapon and industrial systems. Developed primarily for military [1,2,12] and space [2] applications, HIL technology was historically based on the expensive vector computers such as AD 100 [1,2,12] or even the Cray-type supercomputers. The main benefit

* Corresponding author. E-mail: ivica.kopriva@public.srce.hr

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of the HIL technology is repeatable non-destructive and non-hazardous prototype testing, verification and validation. This makes it of interest to industrial applications, primarily for the automotive industry [3,4,6,10,14]. The main event that enabled the transfer of the HIL technology into the industrial area was the development of cost-effective, computationally powerful microprocessors. In particular, digital signal processors (DSPs) with advanced capabilities necessary for efficient multiprocessor real-time simulations. Examples of such processors are the Texas Instruments (TI) DSPs TMS320C30/C40 [5,11,14]. The HIL simulation based on general-purpose microprocessors for applications of lower complexity levels have also been reported [10].

The main objective of this paper is to report about the hardware and software structure of a HIL simulator designed and implemented in order to facilitate development, modification and testing of various prototype modules in semi-automatic-command-to-line-of-sight (SACLOS) missile systems. In Section 2, a general mathematical model of the SACLOS system is described. The functional decomposition of the system is based on the logically connected physical subsystems. This allows easier multiprocessor model implementation of the various HIL simulation scenarios, as well as better insight in possibilities for the system modernisation. The hardware and the software structure of the HIL simulator is described in Section 3. The reasons for using a multiprocessor board, consisting of 4 TI TMS320C40 DSPs, are pointed out. The basic description of the special purpose A/D and D/A subsystem, signal interface and user interface is also given in this section. The details related to the implementation of the SACLOS system and the results of the several interesting simulation scenarios are discussed in Section 4. Conclusions are given in Section 5.

2. SACLOS system description

SACLOS guidance is one approach to control anti-tank missiles in the short to medium range engagements. In SACLOS systems the operator's task is only to keep pointing tracking telescope to the target establishing a line-of-sight (LOS) between the launching unit and the target. In the LOS guidance scheme, shown in Fig. 1, the missile is automatically guided on a LOS course in an attempt to remain on a line joining the target and the point of control.

The missile infrared (IR) goniometer is mounted alongside the operator's tracking telescope and is collimated to it. While operator tries to keep LOS pointing at the target, the goniometer generates pitch/yaw signals proportional to the missile's (IR missile tracker) displacement from the optical LOS, i.e. the guidance system error. In response to these signals, the automatic guidance system produces acceleration commands, which are sent to the missile via a wire link. In response to these, the missile then accelerates in such a way as to remain on the LOS, i.e. to keep guidance error ε acceptably small.

The acceleration commands sent to the missile are defined in Cartesian (pitch and yaw) co-ordinate system. These commands have to be transformed to the 'body-fixed' co-ordinates for two pairs of fin control. Missile roll attitude (ϕ) is sensed

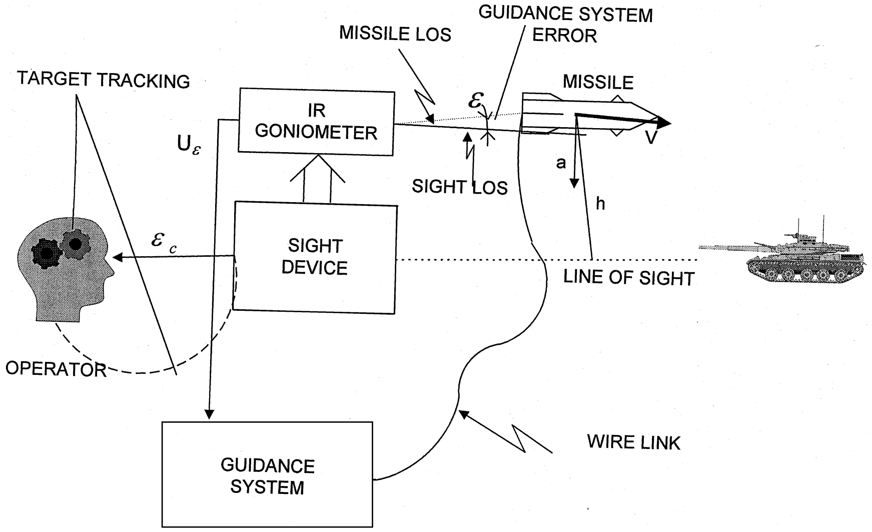

Fig. 1. Semi-automatic CLOS guidance system.

using a gyroscope with a lamellas transformer for distributing guidance signals to the pair of control fins.

2.1. Mathematical models

SACLOS guidance typically includes an up-link to transmit guidance signals from a ground controller to the missile. A basic block diagram of the SACLOS guidance scheme for a rotating missile is shown on Fig. 2.

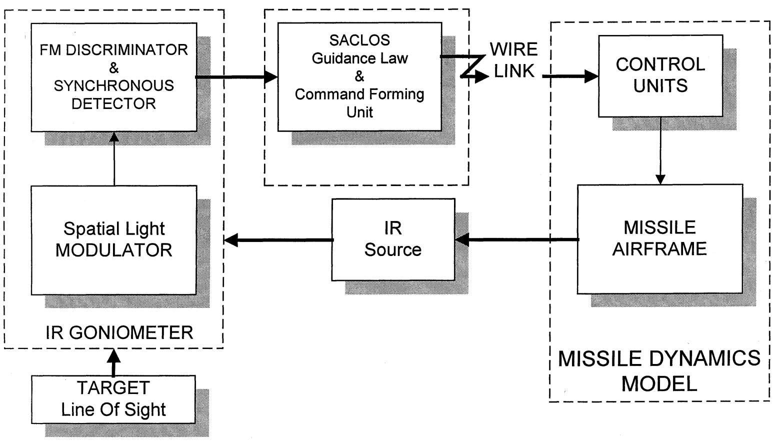

Fig. 2. SACLOS guidance block diagram.

The six degrees of freedom (6DOF) mathematical model of the missile's dynamics is a non-linear model of a flying 'rigid body' object. The general translation and rotation vector differential equations of the flying objects are as follows:

$$m\frac{\mathrm{d}\vec{V}}{\mathrm{d}t} = \vec{F}_\mathrm{a} + \vec{F}_\mathrm{t} + G, \tag{1}$$

$$I\frac{\mathrm{d}\vec{H}}{\mathrm{d}t} = \vec{M}_\mathrm{a} + \vec{M}_\mathrm{t}, \tag{2}$$

where $V = [uvw]^\mathrm{T}$ is the velocity vector, $F_\mathrm{a} = [XYZ]^\mathrm{T}$ the vector of the aerodynamic force, $F_\mathrm{t} = [F_xF_yF_z]^\mathrm{T}$ the thrust vector, G the gravitational force, m the mass of the body, I the tensor of the inertia, H the angular momentum, $M_\mathrm{a} = [LMN]^\mathrm{T}$ the vector of the aerodynamic moment and $M_\mathrm{t} = [L^F M^F N^F]^\mathrm{T}$ the vector of the thrust moment.

Eqs. (1) and (2) are defined in the missile's axis system. For a complete mathematical model of the SACLOS guidance system it is necessary to add equations of the SACLOS guidance law and command forming units, rotating missile control and actuator dynamics as well as the kinematics relations. Thus, the controls of forces and moments have to be added to the right side of Eqs. (1) and (2), respectively. In order to establish the relations between the missile and the target, transformations from the missile's or dynamical (D) co-ordinate to the spherical command point co-ordinate system (C) L_CD have to be used [13].

$$\begin{bmatrix} \dot{R} \\ R\dot{\lambda}_\mathrm{M}\cos\varphi_\mathrm{M} \\ -R\dot{\varphi}_\mathrm{M} \end{bmatrix} = L_\mathrm{CD}V, \tag{3}$$

where R is distance from the command point to the centre of the missile mass, λ_M the missile angle in the horizontal plane and φ_M the missile angle in the vertical plane.

Eq. (3) represents the geometric (kinematics) model. The matrix of transformation can be expressed as a function of the missile attitude angles (Euler's angles ϕ, ψ, ϑ) or alternatively by use of quaternion – parameters (e_0, e_1, e_2, e_3). These quaternions can be computed directly from dynamics Eq. (2), bypassing the computation of transcendental functions needed for computing the Euler angles. In the case when the components of the angular velocities are known in the body co-ordinate system, parameters $(e_0, e_1, e_2, e_3)^\mathrm{T}$ are defined by differential Eq. (4) [8].

$$\begin{bmatrix} \dot{e}_0 \\ \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} -e_1 & -e_2 & -e_3 \\ e_0 & -e_3 & e_2 \\ e_3 & e_0 & -e_1 \\ -e_2 & e_1 & e_0 \end{bmatrix}\begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{4}$$

with,

$$e_0^2 + e_1^2 + e_2^2 + e_3^2 = 1 \tag{5}$$

The four variables e_0, e_1, e_2 and e_3 coupled by means of Eq. (5), uniquely describe the orientation of the missile in space.

A SACLOS guidance law can be described with a very simple model such as a proportional-integral-derivative regulator or with very complex description based on the non-linear inverse dynamics including different compensation forms which would offer potential modernisation of the existing guidance subsystem. The guidance controls expressed in the non-rotating co-ordinate system are transformed to the rotating co-ordinate system using Eq. (6).

$$U_1 = f_1(\phi)U'_H + f_2(\phi)U'_V,$$
$$U_2 = f_1(\phi)U'_V - f_2(\phi)U'_H, \tag{6}$$

U_1, U_2 and U'_V, U'_H are non-rotating and rotating guidance signals for two orthogonal planes respectively. ϕ is the missile rotating angle, $f_1(\phi)$ and $f_2(\phi)$ are modulation functions written as:

$$f_1(\phi) = \frac{1}{2}[\mathrm{sgn}\,(\cos\phi) + \mathrm{sgn}\,(\sin\phi)]$$
$$f_2(\phi) = \frac{1}{2}[\mathrm{sgn}\,(\cos\phi) - \mathrm{sgn}\,(\sin\phi)] \tag{7}$$

Each pair of the fin actuators has a finite bandwidth so that, for simplicity, action of the effective deflection angles can be modelled by a first-order system with surface position saturation and rate saturation.

2.2. Missile localisation system – IR goniometer

In a number of SACLOS systems the missile position is detected by using an IR source, placed in the tail of the missile, in combination with a special electro-optical system, an IR goniometer, that is based on a rotating reticle which is also called a modulating disk [15], Fig. 3. The role of the system, which is based on the rotating reticle and photodetector with appropriate spectral response, is to determine missile position by detecting infrared energy emanating from the missile IR source and to suppress unwanted signals from the background [7].

The rotating reticle modulates incident optical flux and is located at the focal plane of an optical imaging system. A photodiode detects the modulated optical signal, where modulating function $s(r, \varphi, t)$ is a function of the polar co-ordinates

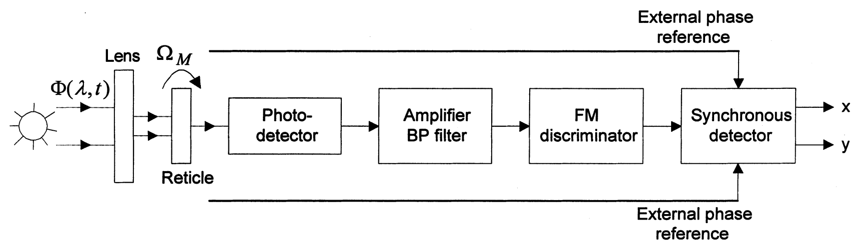

Fig. 3. IR goniometer for missile localisation.

of the projection of the IR source on the modulation disk area and also a function of the reticle type. Here r stands for the modulus and φ stands for the angle. For a reticle with fan-bladed pattern [15,9,19] the modulating function has the form:

$$s(r, \varphi, t) = \cos\left[\omega_0 t - \beta \sin\left(\Omega_M t - \varphi\right)\right] \tag{8}$$

which is a canonical representation of the frequency modulated (FM) signal, [20]. β, ω_0 and Ω_M are functions of the IR source co-ordinates and the optical modulator construction constants. It can be shown, [9,19], that deviation of the FM signal Eq. (8), β, is directly proportional with the polar co-ordinate r. The role of the FM discriminator, see Fig. 3, is to demodulate the FM signal Eq. (8). The amplitude of the demodulated signal will be directly proportional with the r co-ordinate while the phase will represent the φ co-ordinate. By providing external phase reference, the demodulated signal is transformed at the synchronous detector from polar to Cartesian co-ordinates. In reference to Fig. 2, it must be observed that the FM signal Eq. (8) has a much wider spectral bandwidth than all the other signals in the guidance and control loop. Depending on the amount of maximal missile displacement r, the effective signal bandwidth can be as large as 50 kHz, which will influence the design of the signal interface discussed in Section 3.2.

The process of FM signal demodulation as well as synchronous detection can be carried out digitally. This is one important aspect of the SACLOS system modernisation. By application of the HIL simulation the new digital solution can be tested and verified with a real electro-optical system included in the closed guidance loop. Furthermore, since the described type of missile localisation system is sensitive to certain types of IR jamming [19], new advanced signal processing methods [16] can be applied and tested in order to increase the IR jamming margin. The research and development in this field would be practically impossible to carry out without extensive use of the HIL simulation technology.

3. Hardware and software structure of the implemented HIL simulator

The main part of the HIL simulator is an industry PC chassis containing a standard Pentium 200 MHz motherboard, a multiprocessor PC board for digital signal processing and two PC boards with I/O subsystem. The host processor (Pentium) is used for code developing and downloading to the target DSP board, and for both simulation control and output data analysis.

This HIL simulator is primarily intended for laboratory testing and development purposes, thereby requiring some adaptation of the SACLOS system optics, designed for distances between 100 and 2000 m. With a small lens attached to the optics of the SACLOS launching unit real focus distance is corrected to a laboratory distance of 8 m between the launching unit and a plotter. A high-speed (compared to the missile dynamics) A3 plotter with a light emitting diode (LED) of appropriate

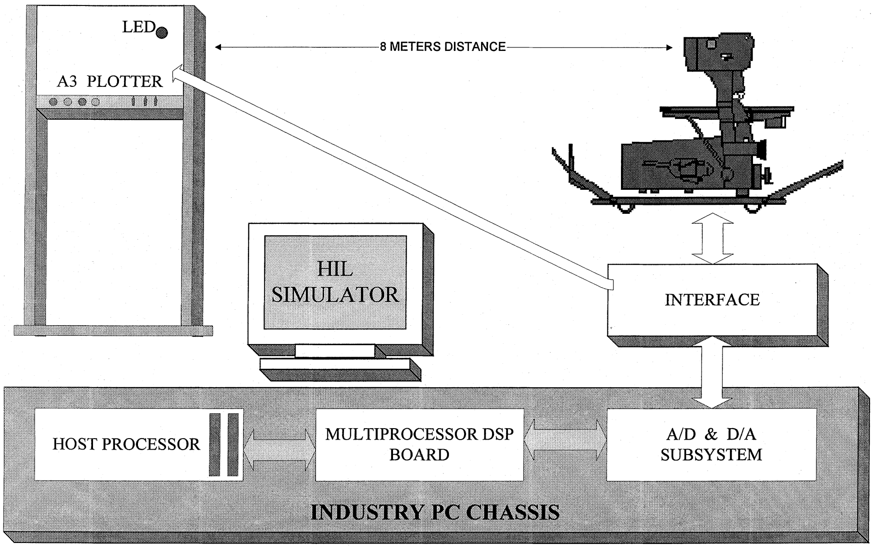

Fig. 4. Hardware structure of the HIL simulator.

spectrum is used as a low cost emulation of the moving missile's IR source. Information about actual co-ordinates of such an IR spot in relation to LOS is produced by a 6DOF missile model and sent to the plotter's analog inputs.

A custom signal interface between the real hardware of the SACLOS system's launching unit and simulator's I/O subsystem also had to be designed.

This hardware structure (Fig. 4) makes a closed guidance and control loop (IR spot – launcher optics – launcher hardware – simulator models – 6DOF missile model – IR spot co-ordinates), and provides platform for a realistic and modular testing as well as for a partial development and modifications of the SACLOS systems.

3.1. DSP board with four TMS320C40

The main processing unit of this simulator is a single PC board that carries four TIM 40 modules [18], each with one TMS320C40 digital signal processor [21] and three 32 kword RAM blocks (see Fig. 5). The C40 processor has six communication (COM) ports, each with assigned direct memory access (DMA) coprocessor. The COM ports, that are essential for modular structure and inter-processor communication are brought to the end-plate connectors.

The communication with the PC host processor is handled via Link Interface Adapter, and development debugging via JTAG standard connector. All processors use the same clock generator, and their execution can be controlled through the user-defined interrupt status flags. The whole system has a performance of 1 GOPS operating on a 50 MHz clock.

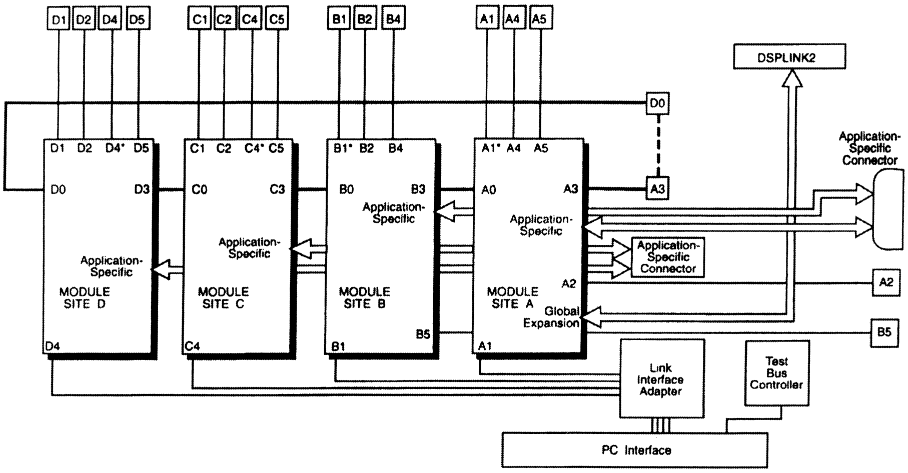

Fig. 5. QPC/C40B multiprocessor PC board with four TIM modules.

The COM ports are connected in each-to-each-other mode that offers maximum flexibility for data-exchange and for implementation of the simulation models, which due to the different HIL simulation scenarios require modifications of the simulation structure.

This modularity and flexibility of the multiprocessor platform makes the functional decomposition of a real system transparent to the simulation hardware, thereby reducing the complexity of implementation and context switching between different scenarios in a complex HIL simulation.

One port from each processor is connected to LIA connector, thereby enabling direct communication between the host and each signal processor. This provides facility for code and data downloading, as well as for exchange of data and control parameters during or after simulation process.

Inter-processor communication is carried out through DMA channels, enabling asynchronous high-speed data transfer. Each DMA channel is virtually divided in two channels (split mode) through which data exchange between simulation models, i.e. corresponding processors, is carried out (Fig. 6). All necessary data are exchanged between pre-assigned memory locations, concurrently with the execution of the main program (see Fig. 6). This construction provides a platform for a smooth communication between simulation models that are discretized with various periods, since high-speed data exchange is carried out by DMA completely independent from their execution.

If, for example, model A with a shorter deadline sends data to a slower model B (longer deadline, i.e. discretization period), model B uses the newest data from the memory, i.e. the most recently received. On the other hand, if a model B is faster, prediction with data extrapolation can be done according to the memory record of the two-three or more previously received data. This provides updated data for

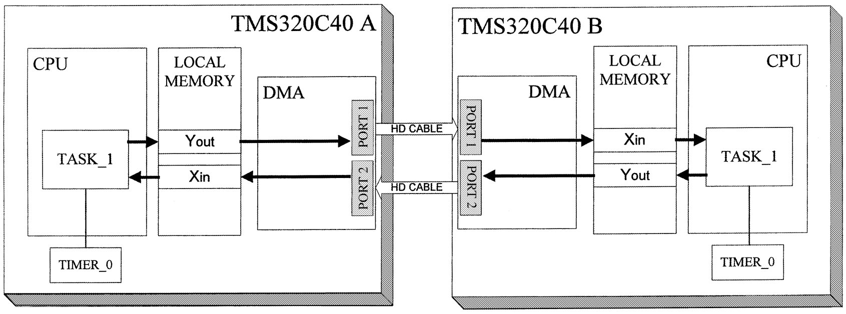

Fig. 6. Asynchronous communication model.

each step of the faster model execution, instead of using the same data from the slower model a number of times.

This feature is of essential importance for efficient multi-rate real time simulation of complex dynamic systems [11] such as the SACLOS system described in Figs. 1 and 2 and by Eqs. (1)–(8), when deadlines of each implemented model are functions of the dynamics of the correspondent physical subsystem.

Determinism of the whole simulation is maintained by using user-defined status flags for synchronisation and simultaneous execution start of all models together using the distance counter start signal that comes from the SACLOS launching unit.

3.2. I/O card and signal interface

From Fig. 4 it is clear that the design of a custom signal interface was necessary in order to connect the HIL simulator with various types of analog signals that exist at the appropriate connection points of the real SACLOS equipment. Depending on the chosen HIL simulation scenario different types of analog signals must be converted to the digital domain and vice versa. The main roles of the signal interface design are: to adjust voltage range of the selected signals to the voltage range of the A/D and D/A converters; to transform signals from differential to single-ended formats and vice versa; to electronically isolate appropriate physical subsystems which are simulated or not used from the other physical subsystems that are included in the selected HIL simulation scenario. It is clear from the previous discussion that besides the signal interface, special care had to be paid to the I/O (i.e. A/D and D/A) subsystem. Since effective signal spectra vary from several tens of Hz (guidance signal and missile position signals) to almost 50 kHz (FM signal produced by the electro-optical subsystem) a very wide range of conversion speeds was necessary. When the FM signal is digitised, phase linearity of the antialiasing filter is required in order to synchronise the discriminated signal with the external phase reference signals. Therefore, a $\Sigma\Delta$ type of A/D converter had to be used with a digitally realised over-sampled FIR antialiasing filter. Since a half of a $\Sigma\Delta$ converter sampling frequency is 32 kHz, and maximum frequency of the sampled FM signal is around 29 kHz, no analog antialiasing filter with maximally flat group delay could meet such a narrow transition band requirements. The ratio between the required minimal and maximal conversion speeds was approximately 1 : 1000. Since, in a case of ΣΔA/D converters, sampling frequency can vary with a typical ratio of 1 : 10 between minimal and maximal sampling frequency, it was possible to cover the conversion range between approximately 10k samples and 100k samples.

Another type (successive approximation) of A/D converters was necessary for the low conversion speeds covering range from 100 samples to 20k samples. Consequently, the I/O card consists of two 12-bit successive approximation type of A/D converters, two 16-bit ΣΔtype of A/D converters and four D/A converters with appropriate pre- and post-filters. Each pair of A/D and D/A converters is connected with its own TMS320C40 signal processor on the processor board. Consequently, two of the six communication channels on each processor are devoted to the communication with the analog world. Configuration of the A/D and D/A channels as well as the data format conversions is performed by programmable logic (ALTERA 128 cells EPLD chip). Since it was very difficult to find such A/D and D/A card on the open market it also had to be designed to complete the HIL simulator.

3.3. User-interface and software support

Software support includes Texas Instruments C40 Compiler, Assembler, and Linker [22] together with DB40 debugger and C40 API support [17].

In order to facilitate the various phases present in a complex HIL simulation scenarios, a graphical user interface called 'TMS320C40 integrated development environment' (IDE) has been built (Fig. 7). It integrates all the previously mentioned software packages with many additional options.

This IDE is user-friendly windows environment, written in Microsoft Visual C/C++, and enables writing, compiling, debugging and running of code. All settings for incorporated software can be made through windows box checks. The basic IDE appearance is very much alike the common C/C++ environment.

Code is supposed to be written and tested for each processor independently, but it can be run on a single processor or as a package for all four processors. All of the six simulation modes, and one custom mode can be defined in the 'Multiple run' window shown on Fig. 7. In this window the user can specify which model to run on which processor (according to the desired simulation mode) and also to specify where to store the control data and the simulation parameters. The data format can be also specified (hexadecimal, integer, floating-point). After pressing the OK button, the code for all four processors will be downloaded, and prepared for synchronous start.

Then synchronisation of code execution on all four processors is provided by START signal driven by the launching unit's trigger (start of the launching process), or from the button on I/O interface for testing purposes.

This environment fully supports all features and modes of this HIL simulator, and also provides an easy-to use GUI for all users. Some features of the IDE itself

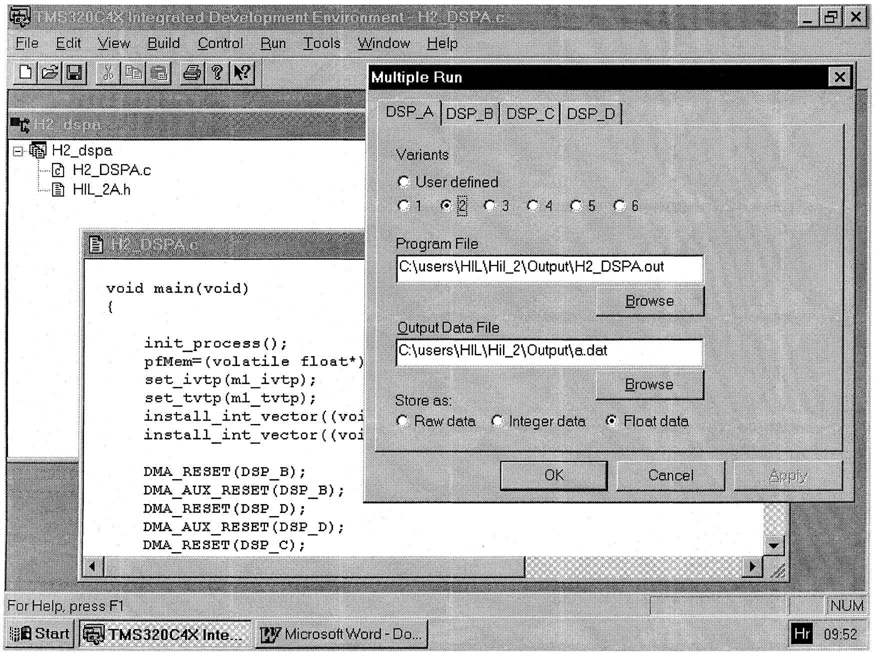

Fig. 7. IDE graphical user interface outlook.

were not previously implemented, even by the software support manufacturer. For example windows settings and execution with message boxes for the TI C40 Compiler, assembler and linker as well as windows support for using LSI's API libraries.

3.4. HIL simulation results

As already pointed out in the second section, two main candidates for the possible modernisation of the described SACLOS system are the missile localisation subsystem (IR goniometer) and the guidance subsystem (see Fig. 2). Based on the layout shown in Fig. 2, complex mathematical models of the three subsystems had to be implemented on the DSP platform in order to perform the related HIL simulation. These are the 6DOF model of missile dynamics; the SACLOS guidance law with the command forming unit and the FM discriminator and synchronous detector. Details related to the TMS320C40 implementation of each of these models are given in Table 1. Deadline times are equal to the discretization periods of each model, determined by a model's dynamics, and must be met during simulation to maintain hard real-time constraints. Execution times are actual times required by the TMS320C40 processor to pass the longest execution path of each model code.

Table 1

Model	Deadline time	Execution time
6DOF model of missile dynamics C language	2 ms	0.6 ms
Guidance law and command forming unit C language	2 ms	38 μs
Digital co-ordinator (FM demodulator and synchronous detector) Assembly language	16 μs	14.7 μs

Fig. 8 shows the physical mapping of these models on the QPC/C40B multiprocessor platform needed to perform the HIL simulation and to verify a new digital solution of the IR goniometer and guidance as well as the control subsystem.

The FM discriminator and synchronous detector are placed on one processor – DSP C in Fig. 8 under the name 'digital co-ordinator'. The 6DOF model of missile dynamics is placed on DSP A, while the SACLOS guidance law and command forming unit are placed on DSP D, under the name 'digital guidance system'. The main feature of this simulation scenario is that processing of the FM signal produced by the spatial light modulator (IR goniometer) as well as the synthesis of the guidance and command law, are performed in a digital manner. The FM signal demodulation described with Eq. (8) is performed by the quadrature signal processing techniques.

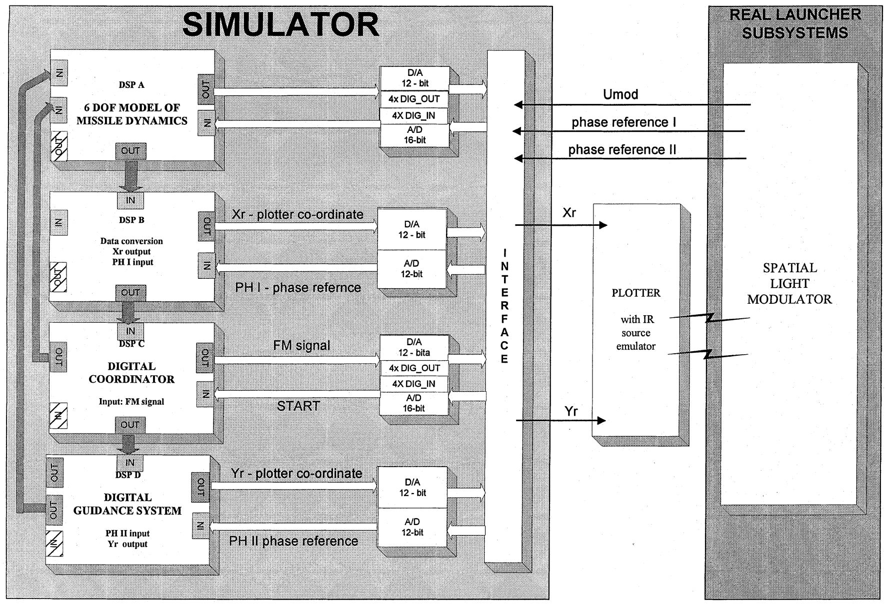

Fig. 8. Physical implementation of the second HIL simulation scenario.

The digital FM demodulator, in combination with the digital implementation of the synchronous detector, extracts the Cartesian co-ordinates of the IR source projection on the plane spanned by the modulation disk. The co-ordinates are defined in relation to the centre of the modulation disk. On the basis of these co-ordinates, which represent instantaneous guidance error, guidance law and command forming units synthesise the command in order to reduce that guidance error. In this simulation scenario, synthesis of the guidance and command law is performed by simple digitisation of the existing analog control law, whereas in the missile localisation subsystem new algorithms were applied. The main feature of this version of the HIL simulation is flexibility. It permits future modernisation of the SACLOS system by developing new guidance and control laws as well as by enhanced signal processing methods related to an increasing IR anti-jamming capability [16].

The instantaneous guidance error relative to LOS in both vertical and horizontal plane is reported as a final performance measure in Fig. 9. Acceptable error for typical SACLOS system varies from 1.5 m in vertical plane and 1 m in horizontal plane in the beginning phase of the missile flight to 0.5 m in both planes in the active phase of the missile flight (i.e. with declared hit probability, 500–2000 m).

As can be seen from Fig. 9, in our simulation the guidance error in vertical plane after fourth second of flight exceeds declared 1 m diameter tunnel. This is caused by the inherent error related to the present laboratory environment. As discussed in Section 3, a correction of the optical focus from the real world target distance (800–2000 m for the second optical channel that becomes active after 4 s of flight) to the laboratory distance (8 m) had to be made. Attached lens has significant influence to the magnitude of guidance error after fourth second, when the narrow field of view (second channel) is in use, while it can't be ideally mounted orthogonal to the optical channel line. Therefore, the point source image is not correctly focussed in the centre of the optical channel, and causes an additional constant small angle error in vertical plane (in our example). Since the absolute error (in meters) is computed by multiplying the angle error and the distance to the missile, influence of this additional error is constantly increasing.

This type of error can be avoided by using dynamic collimator for simulating moving missile IR source. However, in relation to the described plotter based solution this would be an extremely expensive solution. Furthermore, since the reference simulation scenario that includes the analog IR goniometer and guidance subsystem is conducted under the same conditions, this type of error has no essential influence on the applicability of the HIL simulation concept in SCALOS system modernisation. In that sense (related to the referent scenario), the reported simulation results of this simulation scenario are considered to be of acceptable accuracy.

To illustrate the influence of the errors introduced by performing experiments with the real electro-optical system, the another HIL simulation was performed. The real IR goniometer is modelled as memory-less linear system. The missile co-ordinates, that are inputs to the guidance law and command forming unit, are obtained by a simple scaling of the missile position obtained from the 6-DOF model of missile dynamics. Synthesis of the guidance and command law is performed in the digital domain in the same manner as in the basic HIL simulation scenario. The guidance

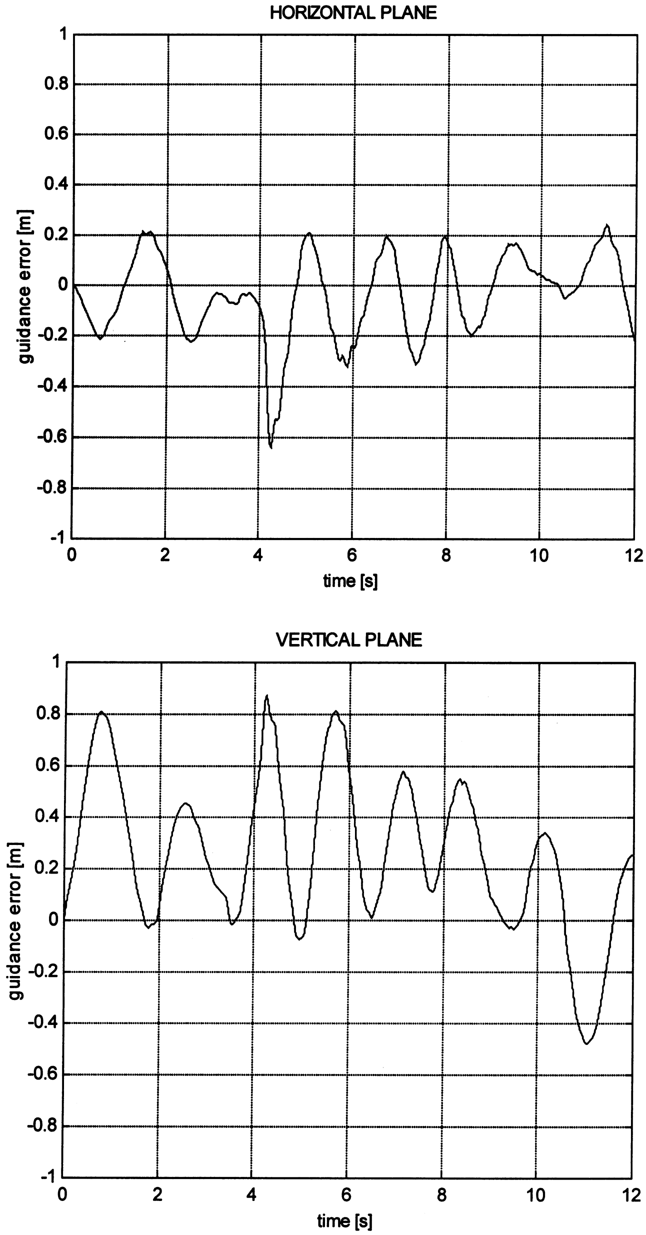

Fig. 9. Guidance error in horizontal and vertical plane.

error in vertical and horizontal plane is shown in Fig. 10. It can be seen that the instantaneous guidance error is inside the specified range. Moreover, direct comparison of the Fig. 9 shows that dynamic behaviour of the guidance error in the first

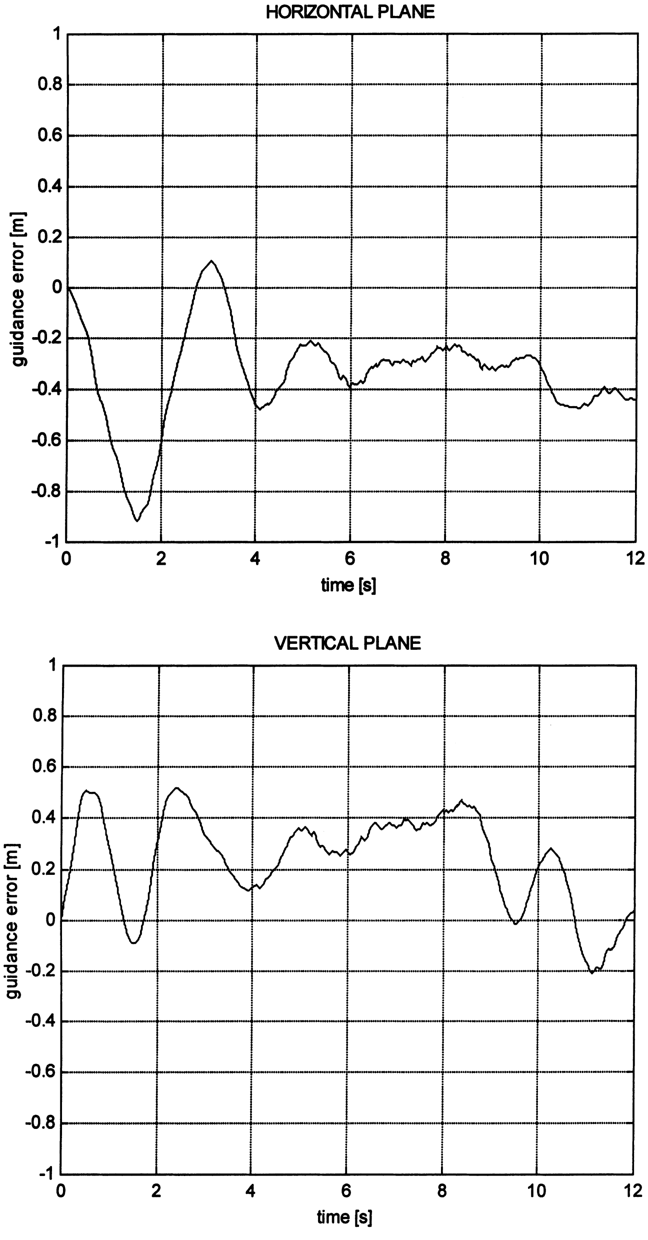

Fig. 10. Guidance error in horizontal and vertical plane.

4 s is very similar in both cases. After the fourth second, however, the discussed optical problems cause guidance error in first HIL simulation scenario to exceed the expected range.

4. Conclusion

The design and implementation of the hardware-in-the-loop simulator for typical SACLOS missile system has been described. The basic structure of the SACLOS missile system has been briefly discussed and possibilities for system modernisation are pointed out. Special attention has been given to the role of the state-of-the-art simulation platform based on cost-effective multiprocessor PC board, consisting of 4 TMS320C40 digital signal processors, in the efficient multi-rate real time simulation of such a complex dynamic system. Details related to the implementation of the simulation scenario significant for the modernisation of the SACLOS missile system as well as the main simulation results are also reported. Consequently, the importance of the HIL simulation technology to the modernisation phase of the discussed system has been clearly illustrated. It has been demonstrated how a HIL simulation approach based on a cost-effective computational platform can reduce development costs related to a design of quite complex weapon system such as the described SACLOS missile system.

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