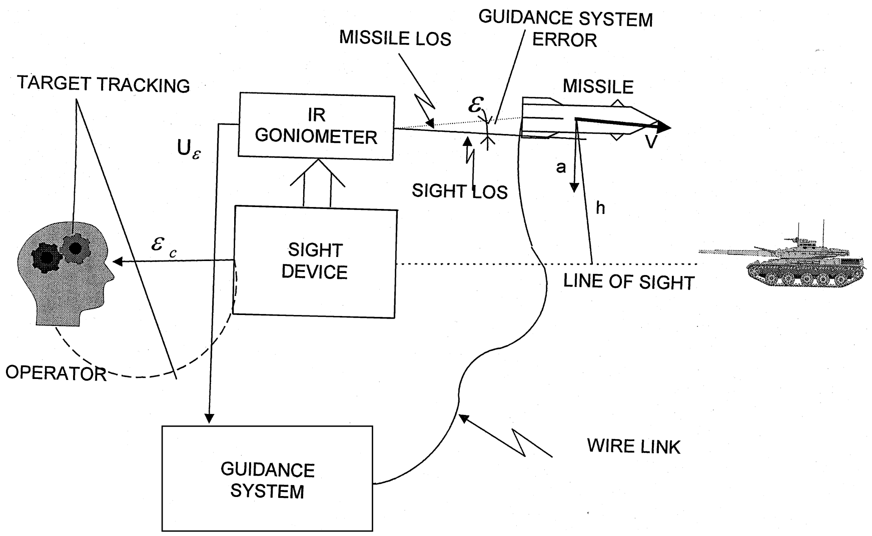

Fig. 1. Semi-automatic CLOS guidance system.

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.

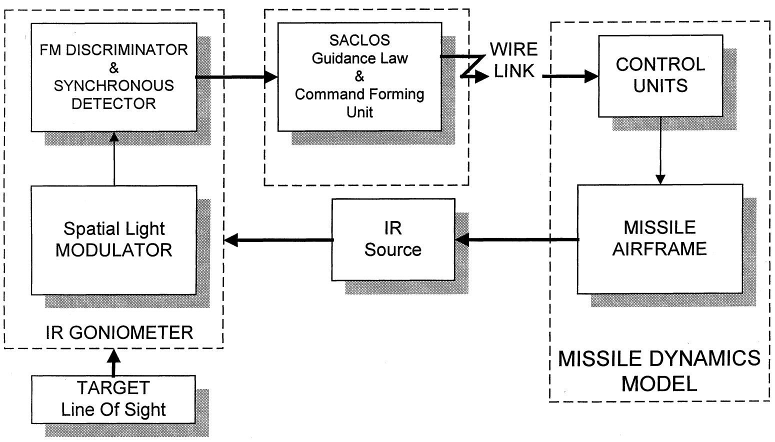

Fig. 2. SACLOS guidance block diagram.

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:

$$m\frac{d\vec{V}}{dt} = \vec{F}_a + \vec{F}_t + G, \tag{1}$$

$$I\frac{d\vec{H}}{dt} = \vec{M}_a + \vec{M}_t, \tag{2}$$

where $V = [uvw]^T$ is the velocity vector, $F_a = [XYZ]^T$ the vector of the aerodynamic force, $F_t = [F_xF_yF_z]^T$ the thrust vector, G the gravitational force, m the mass of the body, I the tensor of the inertia, H the angular momentum, $M_a = [LMN]^T$ the vector of the aerodynamic moment and $M_t = [L^F M^F N^F]^T$ 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].

$$\begin{bmatrix} \dot{R} \\ R\dot{\lambda}_M \cos\varphi_M \\ -R\dot{\varphi}_M \end{bmatrix} = L_{CD}V, \tag{3}$$

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 $(e_0, e_1, e_2, e_3)^T$ 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).

$$U_1 = f_1(\phi)U'_{\mathrm{H}} + f_2(\phi)U'_{\mathrm{V}},$$
$$U_2 = f_1(\phi)U'_{\mathrm{V}} - f_2(\phi)U'_{\mathrm{H}}, \tag{6}$$

U_1, U_2 and $U'_{\mathrm{V}}, U'_{\mathrm{H}}$ 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

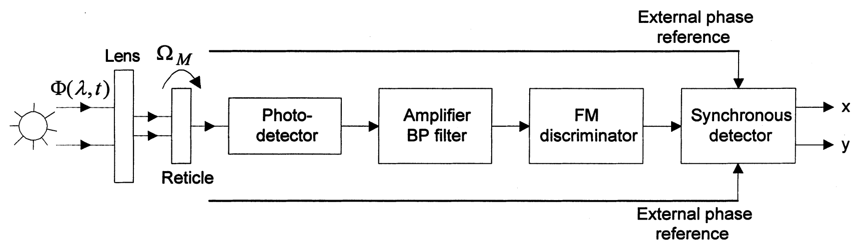

Fig. 3. IR goniometer for missile localisation.

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:

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

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 coordinate 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

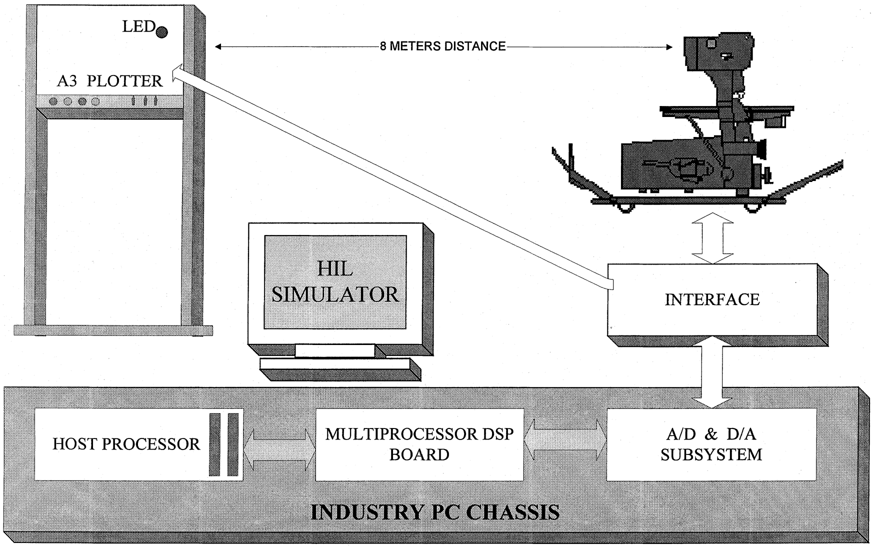

Fig. 4. Hardware structure of the HIL simulator.

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.