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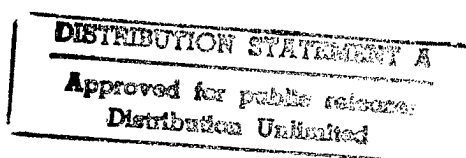
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Abstract

The Highly Integrated Spinning Projectile (HISP) concept minimizes the mass, complexity, and cost of an exoatmospheric homing projectile by using spin to provide an intrinsic inertial reference and target image flow to derive guidance and control. A compact electronic and/or optical computer network performs all guidance, control, inertial referencing, and target tracking functions by converting focal plane target image trajectories into divert thruster commands. Separate inertial guidance sensors are eliminated, fine thruster control is not required, focal plane quantization tolerances are relaxed, and closed-loop operation permits a simple four thruster design with looser design tolerances. The trick is to develop guidance and tracking algorithms which fully utilize the minimal HISP hardware. A computer simulation of HISP dynamics and target track processing confirmed the feasibility of HISP. Recent advances in low-cost electronics provide an opportunity to realistically model all essential elements of HISP in a modest hardware-in-the-loop experiment which exploits the synergism between hardware and software simulations. Physical hardware replaces simulated projectile dynamics and target imagery, allowing realistic performance evaluation of HISP guidance and control algorithms. The long-term goal is a low-cost, low-mass, survivable production model HISP which derives homing and control commands solely from a focal plane sensor and a modest integrated processor.

Introduction

The Highly Integrated Spinning Projectile (HISP) concept minimizes the mass, complexity, and cost of a space-based homing projectile by using spin to provide an intrinsic inertial reference as well as dynamical stability. Figure 1 shows the hardware elements of HISP. A compact electronic and/or optical computer network performs all guidance, control, inertial referencing, and target tracking functions by converting focal plane target image trajectories into divert thruster commands. Separate inertial guidance sensors are eliminated, fine thruster control is not required, focal plane quantization tolerances are relaxed, and closed-loop operation permits a simple four thruster design with looser design tolerances.

Previously, a computer simulation of HISP dynamics and focal plane target tracks verified the feasibility of HISP. Projectile mechanical parameters and tolerances were derived for a baseline engagement sce-

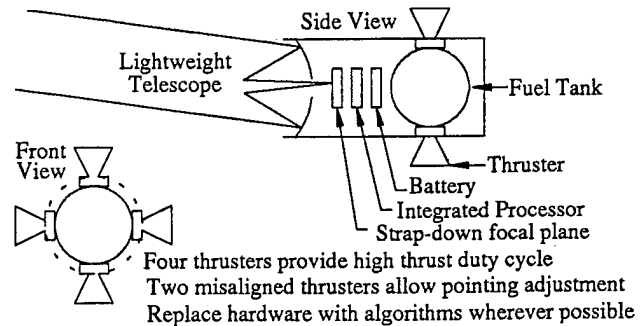


Figure 1. Essential HISP Hardware Configuration

nario. The key problem of thruster timing for a spinning projectile without gyros or accelerometers was solved. An algorithm of modest computational complexity was developed for target line-of-sight (LOS) rate extraction. A video camera/frame-grabber focal plane processing simulation provided insight into practical implementation problems.

Several promising innovative techniques and technologies for HISP guidance and control were identified (including optical processors, Fourier image transforms, neural networks, and adaptive compensation for manufacturing errors). Further research into the relative merits these techniques requires a more realistic simulation. Computer simulation costs and error rates typically increase geometrically as more real-world effects are included, and it is not always clear which effects are most important. Fortunately, recent advances in low-cost electronics and miniature video cameras provide an opportunity to realistically model all the essential elements of HISP in a modest hardware-in-the-loop experiment which exploits the synergism between hardware and software simulations. Physical hardware replaces the computer simulation of projectile dynamics and target imagery, allowing realistic performance evaluation of prototype HISP guidance and control algorithms.

This research is directed toward significant size and weight reduction of homing projectiles without compromise of performance (for bright targets). This increases the amount of maneuverability obtainable from a fixed projectile launch mass with any given level of propulsion technology. Component reduction and near-autonomous operation enhances survivability. The approach utilizes a two-dimensional focal plane array which could also be used for emerging image processing and pattern recognition techniques. No in-flight communications links are necessary since cooperative targeting can be accomplished before launch.

LOS Rate Guidance for a Spinning Projectile

Figure 2 simulates the typical target line-of-sight image trajectory on the HISP focal plane sensor. The small circles are formed at the 30 Hz nominal spin rate of the HISP projectile. The radius of these spin circles is proportional to the pointing offset between the instantaneous projectile spin axis and the target line-of-sight. The instantaneous spin axis nutates at an approximate 1 Hz rate about the axis of (cylindrical) symmetry of the projectile which is nominally through the center of the focal plane. The nutation radius is proportional to the angle between the axis of symmetry and the angular momentum of the projectile. The radii and phase offsets of the spin and nutation are an unpredictable (bounded by manufacturing tolerances) function of the pointing adjustments and course corrections of the projectile. Therefore, a wide variety of spin and nutation patterns are produced on the HISP focal plane.

Unfortunately, the gross structure of the spin and nutation patterns contains no information which can be used to guide the projectile to the target. Only the growth (or shrinkage) rate of the spin circles contains guidance information. Typically, the radii change by about one half of a pixel per second or 1/60 of a pixel per spin (The growth rate in Figure 2 is exaggerated.). The success of HISP is based on finding an algorithm which can filter out the gross structure of Figure 2 and estimate the spin circle growth rate at about five or ten times a second.

The spin circle growth rate directly relates to the target/projectile line-of-sight rate (relative to the inertial system defined by the angular momentum of the projectile). Many different guidance algorithms have been developed which use target LOS measurements to hit

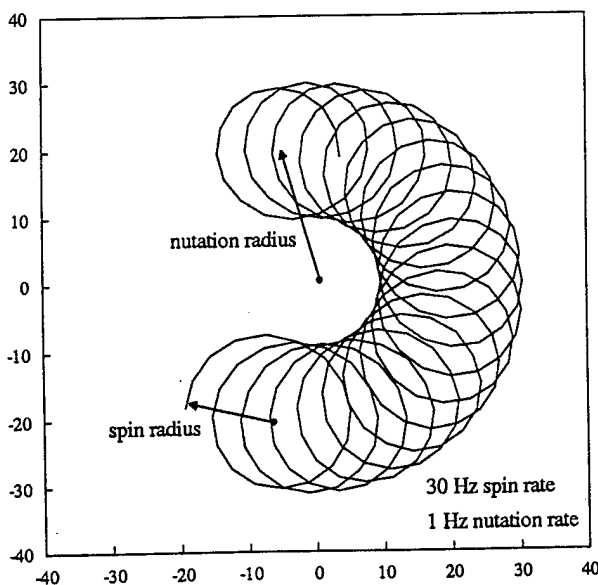


Figure 2. Typical HISP Target Image Trajectory

targets with various amounts and patterns of acceleration. The HISP project did not try to reinvent guidance algorithms for accelerating targets. Instead, the HISP project focused on improving the accuracy and speed of target LOS estimates which are used as input to guidance algorithms. HISP simulations used a simple constant velocity target model to avoid confusing target LOS measurement problems with guidance algorithm target prediction problems. Accelerating targets can be handled by biasing target LOS rate thresholds to account for predicted target acceleration.

Figure 3 shows that the interceptor is on a collision course when the target LOS angle as observed by the interceptor is constant. Figure 4 shows that the interceptor is not on a collision course when the target LOS angle is changing. A constant spin circle radius is observed when the target LOS angle is constant. Therefore (for a non-accelerating target) the guidance algorithm fires the thrusters so as to produce a constant spin circle radius. The slow nutation of the spin circles does not change the average radius of the spin circles.

Now that we know how to transform the target image trajectory into line-of-sight rate guidance input, we must figure out when to fire the thrusters to divert the projectile in correct direction. Figure 5 demonstrates how to fire the thrusters at the right moment to chase the target. If the spin circles are decreasing in radius, the inertial target spot velocity (and perpendicular component of the target velocity) is directed toward the center of the spin circle. The projectile waits for the target spot to reach a maximum (or minimum) along the thruster axes and then fires the opposite thruster to chase the target.

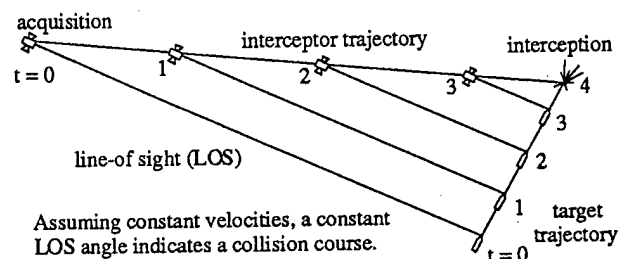


Figure 3. Constant LOS Angle on a Collision Course

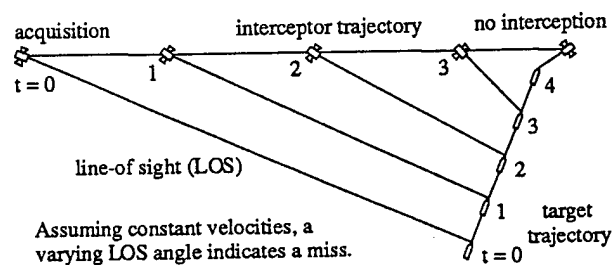


Figure 4. Varying LOS Angle when Off-Course

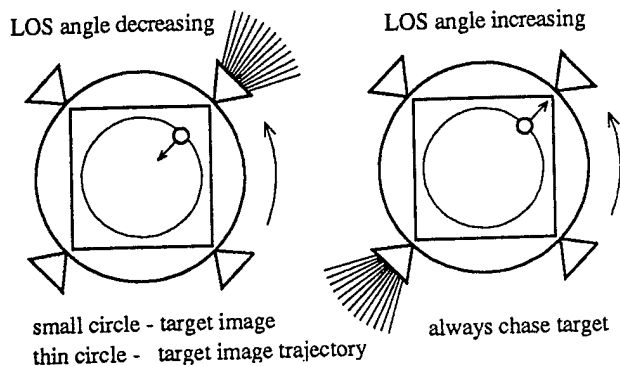


Figure 5. Thruster Phasing Solution

The process is repeated until the target trajectory spin circles exhibit a constant radius. The duration of the course correction depends on the estimated distance to the target and the magnitude of the measured LOS rate.

HISP Guidance and Control Processing

The major processing functions of a spin-stabilized homing projectile are summarized as follows:

1. Sense the presence of the target on the focal plane.
2. Adjust pointing angle to keep target inside the FOV.
3. Derive the inertial LOS rate from target image track.
4. Stabilize the LOS rate filter if target drifts off sensor.

5. Detect and compensate a variable spin rate.
6. Fire body-fixed thrusters at correct time for homing.
7. Reacquire target if thrusters perturb pointing angle.
8. Passive cooperative multi-targeting (optional).

Figure 6 shows a simple algorithm which filters the spin circle radius (squared) from the target image (x,y). The operations consist of a modest number of adds and one multiply. The operation rate is decimated from 480 Hz to 120 Hz as the algorithm proceeds. Moments are formed from the output of this processing stage, and a least-squared estimate of the spin circle growth rate is calculated in a separate processing stage. The uncertainty of the resulting target LOS rate estimate is used to avoid firing thrusters when noise dominates the estimate.

Figure 6 also shows the logic used to derive the thruster phasing. The lower processing network detects extrema of the spin circles along the thruster axes. In addition, a predicted value of the next target position is formed to allow interpolation when the target image drifts off the edge of the focal plane. This step prevents the synchronous filter from ringing if data is unavailable.

An artificial neural network was successfully trained to perform processing of Figure 6 (excluding the final multiplication). The slightly improved performance was not worth additional processing complexity.

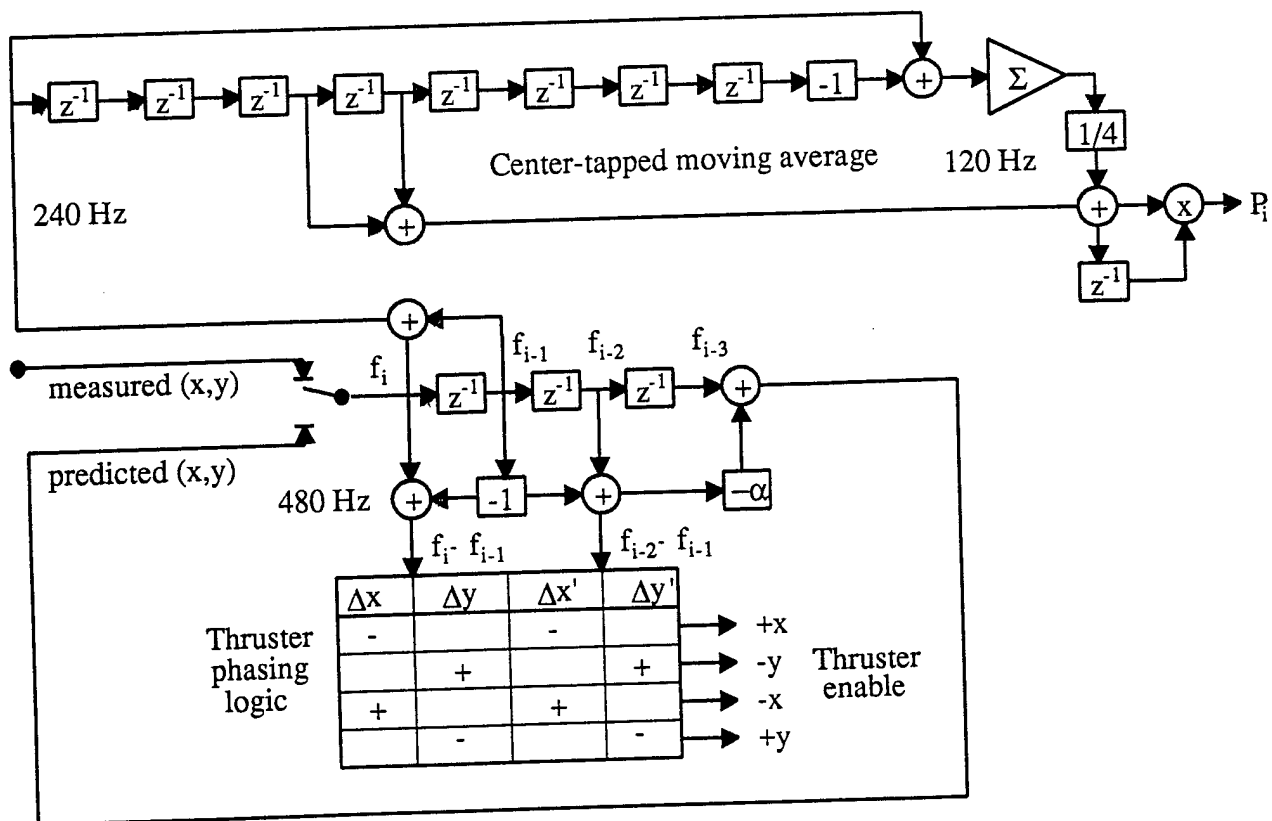


Figure 6. Processing Network for Spin Circle Radius Extraction and Thruster Phasing

An Inexpensive Hardware-in-the-Loop Experiment

Recent advances in low-cost electronics and miniature video cameras provide an opportunity to realistically model all the essential elements of HISP in a modest hardware-in-the-loop experiment which exploits the synergism between hardware and software simulations. Physical hardware replaces the computer simulation of projectile dynamics and target imagery, allowing realistic performance evaluation of prototype HISP guidance and control algorithms. Figure 7 shows the layout of the hardware-in-the-loop experiment.

The model projectile consists of essential hardware components such as a focal plane array, four compressed gas thrusters, and batteries as depicted in Figure 8. It freely rotates and nutates in an air bearing assembly which can translate in a horizontal plane so as to "intercept" the simulated target, a moving laser beam spot projected on the laboratory ceiling. To obtain the flexibility needed for basic research, some processing functions are performed off-board, using remote links to transmit target image video signals and thruster control commands. This novel hardware-in-the-loop experiment sacrifices a small amount of fidelity for an enormous savings in cost over traditional facilities. While the adjective "low-cost" is seldom associated with "hardware experiment", advances in commercial electronics provide a cost advantage over a high-fidelity software simulation.

Some of the cost-saving features of the HISP hardware-in-the-loop experiment are as follows:

1. The projectile spins about a vertical axis to symmetrize gravity perturbations.
2. A laser projects a target spot on the ceiling for easy, effective noise filtering and demonstration clarity.
3. High/low compressed N_2 thrusters are safe, use inexpensive valves, and give ample simulation time.
4. A compact NTSC camera and RF modulator provide inexpensive off-the-shelf image transmission.
5. A model airplane radio-controller makes thruster control inexpensive, low-risk, and lightweight.
6. Power obtained from moveable D-cells also permits balancing and moment ratio adjustment.
7. Use of off-the-shelf microcontroller evaluation boards minimizes risk and facilitates design changes.
8. A coupled spreadsheet design quickly and clearly shows impact of design tradeoffs.

Because HISP performance relies on a maximal algorithm controlling minimal hardware, the enhanced target acquisition and homing techniques resulting from this research are essential to HISP success. Key issues of sensitivity to mechanical imbalances, thruster misalignments, image sensor peculiarities, and variable LOS rate observability will be addressed.

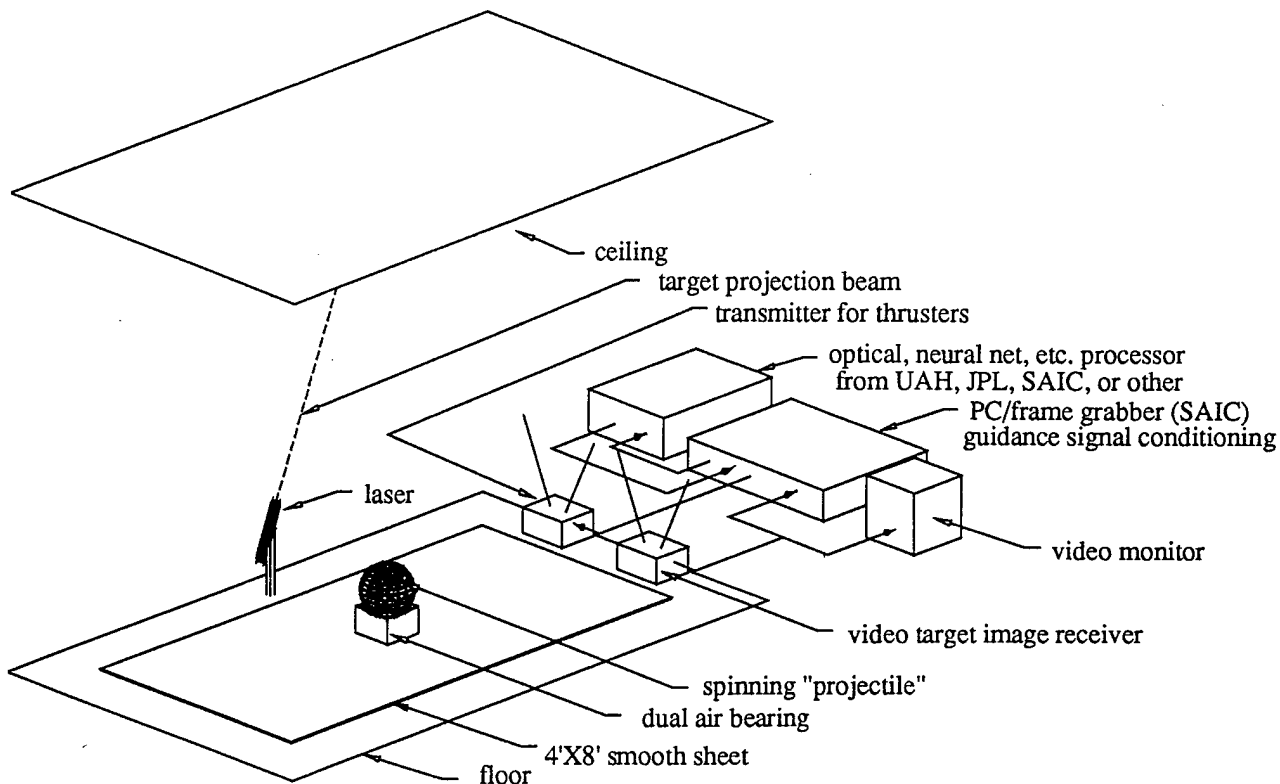


Figure 7. Layout of HISP Hardware-in-the-Loop Experiment

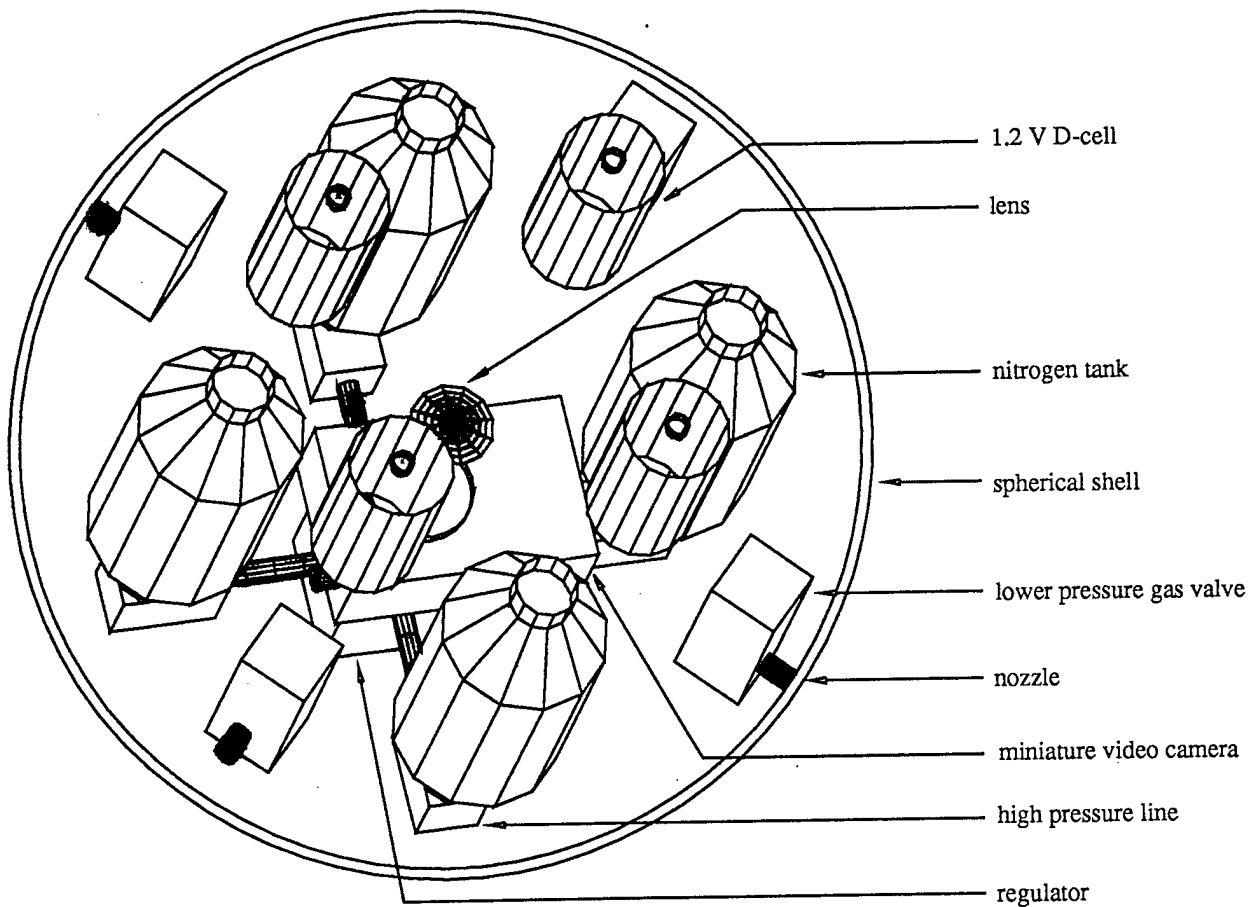


Figure 8. Layout of HISP Experimental "Projectile"

As a bonus, the remote links provide a low-cost capability to realistically evaluate exotic guidance and control techniques from other facilities. Figure 9 displays the modular nature of the HISP experiment. For initial testing, a video tape of target imagery from the testbed sensor can be recorded. This tape could be sent to other facilities to insure compatibility with processing hardware. When the processor has been customized for the typical testbed imagery, off-site experiments using the testbed could (efficiently) proceed. The only signal connections between the processing system and the testbed are standard NTSC video target imagery, and RS-232 serial communications to the testbed microcontroller for thruster commands.

Figure 9 shows a block diagram of the electrical portion of the testbed. At the heart of the system is single 16 MHz Motorola 68332 microcontroller chip (with memory) which features sixteen independently programmable timer channels. The channels can capture events with a resolution of 4 MHz. In addition, RS-232 communications are handled by a separate unit within the chip to further off-load the main processor.

At this time, four of the timing channels are used as input for the NTSC target image video signal and sync signals. The position of the target image centroid is updated at a 60 Hz rate. Four timing channels are used to fire the thrusters (through a remote link). Four other channels are used to generate audio tones as a debugging aid during algorithm development. The other four channels will be used later to control stepping motors which rotate a mirror which in turn directs the simulated target image (laser spot) along the ceiling. The remote electronics fit inside a standard IBM XT compatible case, and use (a small fraction of) the standard IBM XT compatible power supply.

The big advantage to using a microcontroller is that small software control programs are easier to reconfigure than hardware. If the testbed performs well, the powerful microcontroller would make the transition to an autonomous system (no remote links necessary) straightforward. This is outside the scope of the current project. The final step toward realistic projectile electronics would be to replace the video camera with a single focal plane (CCD or CID) chip and a microsequencer to clock the pixels at the proper rate.

The construction of the testbed is about half completed. The double-sided air bearing design and construction seems to be the trickiest remaining problem. A 10 inch diameter aluminum hemisphere will be used as a

foundation for the "projectile". Line current will be used to power the air bearing blowers. If the air bearing becomes too much of a problem, a more conventional bearing system will be used.

1. Use computer scene simulation for input.
2. Use VCR tape from HISP testbed.
3. Use actual testbed HWIL output.

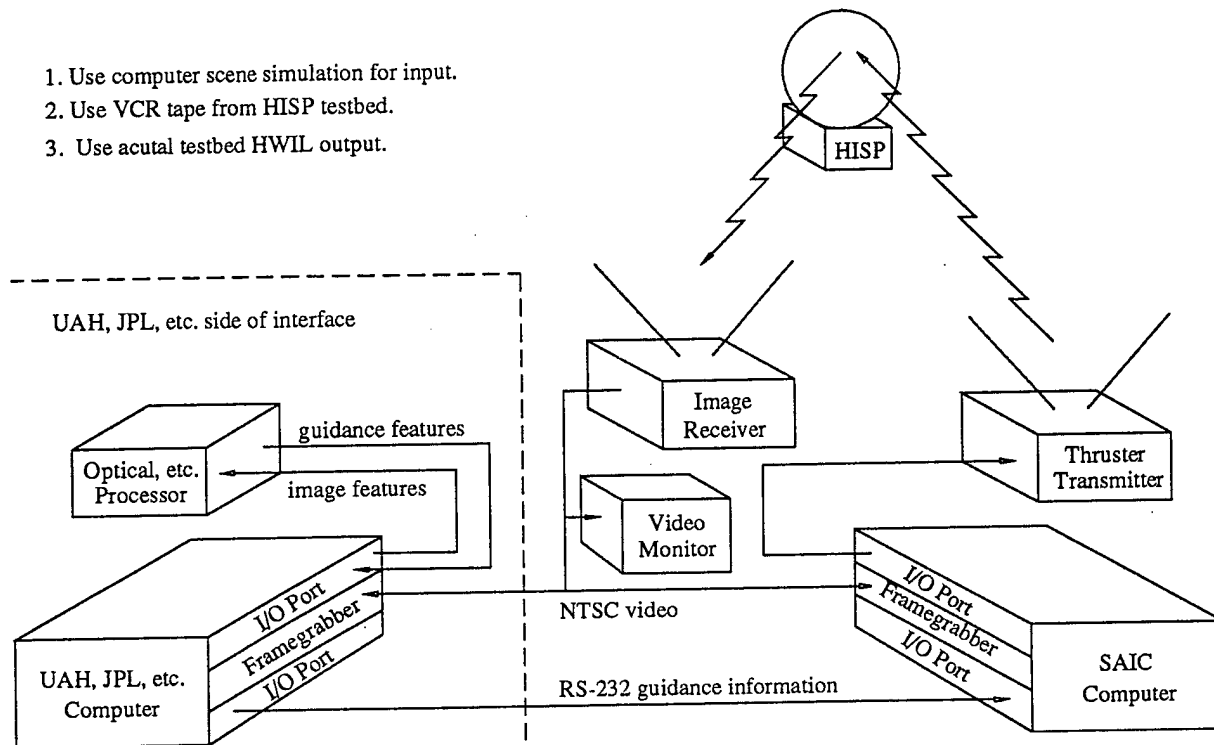


Figure 9. Modular Hardware-in-the-Loop System Allows Easy Testing of Various Guidance Processors

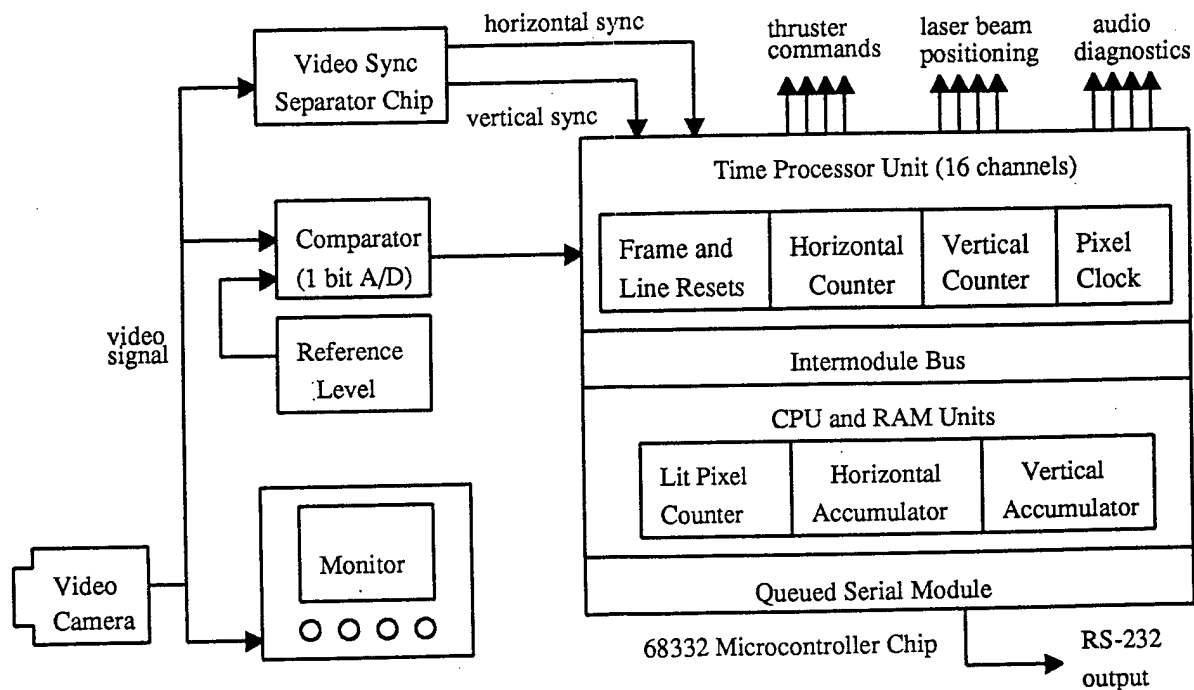


Figure 10. Block Diagram of HISP Experiment Microcontroller Processing

Final Comments

The general realization of integrated guidance and control and signal processing and the successful utilization of a spin stabilized body can open avenues for size and cost reduction without performance compromise in a wide variety of missions. Reduced projectile mass renders advantages in the amount of maneuverability obtainable from a fixed projectile launch mass with any given level of propulsion technology. The miniaturization, cost and performance advantages expected to accrue from this research activity are those sought by many other mission applications including regional defense and other ground and space-based rocket-launched interceptors.

The HISP concept is viable and applicable to brilliant pebble systems by virtue of its potential low mass and loose tolerances. It would be possible to deploy many of these projectiles (brilliant sub-pebbles) so that multiple bullets could be fired at a single target or target cluster. With several cheap projectiles available per target, countermeasures could become prohibitively expensive.

Note that cooperative projectile behavior could be achieved when attacking a cluster of targets without need for communication links. By firing a closely spaced sequence of HISPs along a common spin axis, a target cluster could be partitioned into concentric zones about the center of the target cluster. Each HISP would view the target cluster from nearly identical positions, and hence the zone assignment would be consistent for all attacking HISPs. Before launching multiple HISPs, successive HISPs would be instructed to lock in on the first, second, etc. target observed where the targets are numbered according to their distance from the cluster center. Naturally, some projectiles would be wasted when multiple targets fall within a single zone, but redundant HISP assignments would minimize target leakage. A two-stage attack could be used if the targets exhibited closely-spaced clumps hidden in widely-spaced decoys.

The HISP concept enjoys several survivability advantages relative to other projectiles with homing guidance capability. Fewer components, less payload mass, and the elimination of the gyro subsystem favor increased survivability. The maintenance of ultra precision after the launch environment is generally obviated since the accuracy of pointing angle adjustments typically will not affect the LOS rate measurement accuracy. Since electrical connectors are physically very short, and most of the processing is "hardwired", except for a few gain schedules and thresholds which could be externally refreshed, the susceptibility to nuclear event induced upsets will be minimized.

A spinning focal plane does limit the mission of a HISP projectile. A very faint target signature will be smeared over many pixels making target detection and tracking impossible. The HISP is intended for targets with bright signatures such as typical for boost-phase interception, sunlit targets, or systems using a laser target designator. Another potential HISP problem is the susceptibility of the LOS rate measurement to aerodynamic turbulence in the denser atmosphere. Remember that the angular momentum of the projectile is used for an inertial reference. Turbulence produces torques which alter the projectile angular momentum. Higher spin rates and careful aerodynamic package design could reduce this potential problem.

An advantage of the HISP concept is a reduced LOS rate error since large number of independent pixels are used to generate the measurement. Also tolerances can be relaxed and only four bang-bang (pulse) thrusters are used since measurements are not sensitive to pointing error. Small, compact projectiles should be less sensitive to high accelerations, shocks, thermal cycling, and countermeasures. Finally, the prospect of more projectiles per kilogram allows the use of less complicated passive cooperative schemes which tend to waste projectiles when minimizing leakage.

Acknowledgements

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