System for demonstrating arbitrary multi-spot beam steering from spatial light modulators

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Abstract: A graphical user interface is used to program sequences of analog phase patterns onto a 512 x 512 pixel, electrically-addressed spatial light modulator (SLM). Hand sketches made with a digital pen are used to prescribe the footprints, velocities and trajectories of multiple, independently-controlled diffracted spots. The interface is intended to demonstrate to potential end-users, who are not knowledgeable about diffractive optical design, to what degree SLM's may be considered to produce arbitrary multi-spot beam steering. Using the interface, scanning sequences are created, programmed, run through, and diffracted from a SLM that simultaneously scans multiple patterns on distinct trajectories.

OCIS codes: (230.6120) Spatial light modulators; (050.1970) Diffractive optics; (070.2580) Fourier optics; (120.5800) Scanners; (140.7010) Trapping; (999.9999) Man-machine interface.

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1. Introduction

Two common approaches for the generation of laser patterns and images are scanning a laser spot to trace out a complete image over time, and diffracting a laser beam from a diffractive structure to produce a complete static pattern in one instant. A dynamic laser image, or movie, is produced by sequencing a series of diffractive optical designs through a dynamic diffractive optic, i.e. a programmable spatial light modulator (SLM). Such a system can be used to emulate multi-spot laser scanning or beam steering when the diffraction pattern sequence consists of spots that move on continuous trajectories. Recently, Ge *et al*. experimentally demonstrated a number of multi-spot scan sequences produced by a 120 x 128 pixel phase-only SLM [1]. Most of the diffraction pattern sequences were pre-computed off-line and then run through the SLM in real-time to demonstrate scanning. Of the few patterns that were computed and run in sequence at real-time rates, the spot positions and trajectories were selected in advance and then hard-coded into the multi-spot scanning program.

Additionally, in the field of laser trapping technology, there have been recent efforts at using SLM's in place of mechanical scanners in optical trapping microscopes. While mechanical scanners have demonstrated virtual multi-spot capabilities by rapidly stepping the beam between several locations in sequence [2,3], the use of SLM's provides true multispot beam generation, as well as diffractive generation of vortex beams and even more involved contours [4-6]. While these SLM-based systems demonstrate the great variety of patterns possible from SLM's, their patterns appear to have been computed off-line.

The SLM-based laser trapping system reported by Rodrigo *et al*. [7] is potentially the most easily programmed trapping system because, unlike the SLM-based systems described above, their phase-only SLM is imaged (via phase contrast filtering), rather than Fourier-transformed into the object plane of the microscope. Their interface permits the user to interactively designate and change the position of laser spots using the computer mouse to sequentially perform real-time manipulations of trapped particles viewed under the microscope. While the system has been used to successfully trap and manipulate several particles at once, because it is image-based, it does not use laser energy as efficiently as do the diffractive SLM systems, which are the focus of the present study.

While the various diffractive SLM studies demonstrate that SLM's have great flexibility and a nearly-arbitrary programmability, it does not make that programmability easily accessible to engineers and scientists from outside the optics community. To date, an input interface, especially an interface with real-time pattern creation, has not been a principal focus of the diffractive optics community. Instead most efforts to date have been focused on design of high diffraction efficiency, fixed-pattern optics. Yet a simple interface is needed to truly appreciate the real-time capabilities and varied patterns possible using SLM's.

Our philosophy in developing a real-time interface is similar to the philosophy of the Defense Advanced Research Projects Agency's (DARPA) Transition of Optical Processors to Systems (TOPS) program [8]. The philosophy emphasizes that it is not enough to demonstrate technical performance of an optical processor, but the processor needs to be further developed so that it is easy for the end-user (i.e. the system engineer) to evaluate it for an intended application. Systems engineers who wish to evaluate what a multi-spot steering system is capable of, would be better served if they could directly and simply input their beam steering sequence into the SLM control software. In addition to the evaluation of diffractive beam steering system, sequences designed by systems engineers would improve communications of systems requirements to optical engineers, thereby speeding up enhancements, refinement and specialization of the multi-spot scanning system for the desired end application.

Herein we report on the development of a simple interface that appears useful for the purpose of allowing non-specialists in optical processors to directly evaluate the beam steering capabilities of an electrically-addressable SLM. The input system uses a Logitech pen [9] to select various spot profiles that are to be scanned and to digitally record a sequence of patterns sketched on paper that represents the desired trajectories of each of the spots. On downloading the sketch from the pen to a computer, the desired sequence of diffractive patterns is automatically designed and run through the SLM. This specific interface is intended to demonstrate to the potential end-user our claim (and the limits to our claim) that "diffractive SLM's can produce arbitrary multi-spot beam steering sequences" [10,11]. The remainder of the report describes the interface and input process, then presents example demonstrations of multi-spot beam steering created through the interface and implemented on a recently developed SLM [12,13], and concludes by considering potential extensions of and alternatives to the current interface.

2. Description of the user-to-SLM interface

The Logitech digital pen is integrated with a Labview program that also controls the electrically-addressed, parallel-aligned liquid crystal, 512 x 512 pixel SLM (Boulder Nonlinear Systems 512N15) [13], a frame grabber attached to a black and white video camera in the Fourier plane of the SLM, and a piezomirror (Burleigh PZ-90 together with a RC-44 ramp generator) in a Michelson interferometer (used to measure and calibrate the phase settings at each pixel of the SLM) The piezomirror is blocked by a shutter following the calibration of the SLM. The interface and hardware configurations are presented in Figs. 1,2.

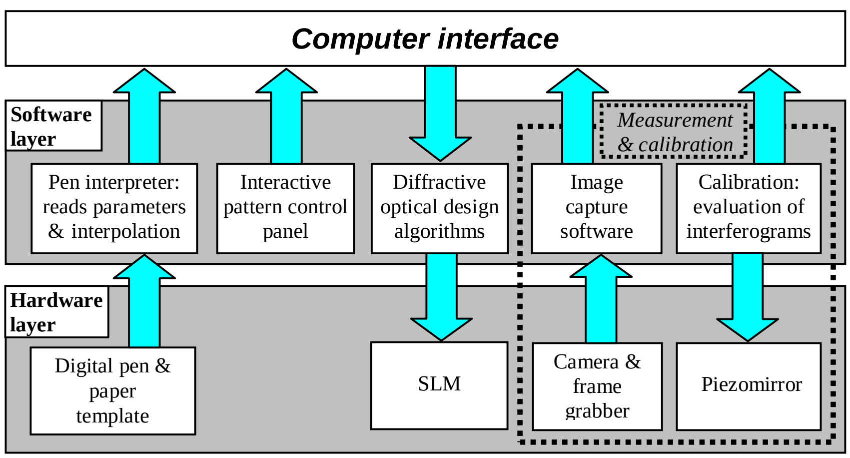

Fig. 1. Schematic of the system for programming multi-spot beam steering sequences onto the SLM. Support hardware and software for calibration and data collection is also shown.

The Logitech pen was selected over other commercial digital pens because it saves a time-sequential record of the pen strokes, which simplifies interpretation. Other digital pens that we considered create image files (e.g. tif and jpg formats) that do not preserve the time ordering. Strokes from computer mice and digital tablets that include pen styluses can be captured in real-time on a computer, thus preserving time-ordering. However, we considered these later alternatives somewhat constraining and intimidating to the casual user for whom

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the system is intended. We feel that pens that permit users to directly input their beam-steering sequences on paper is the most natural and transparent method of demonstrating capabilities of the SLM.

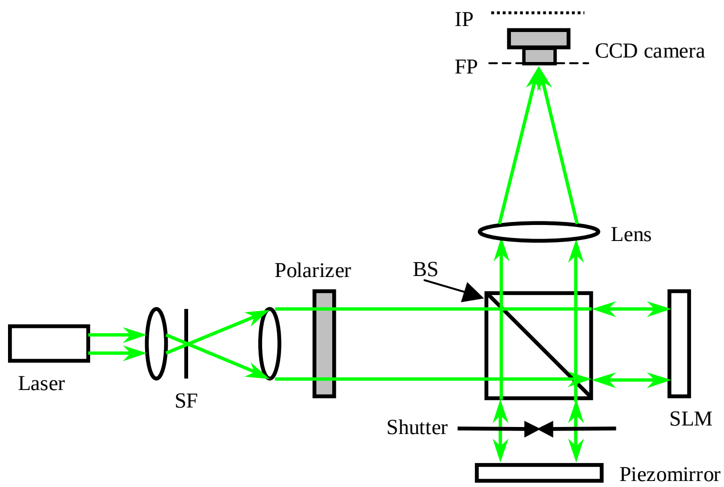

Fig. 2. Schematic of the beam steering optics with the system configured for the beam steering demonstrations. During calibration the shutter is opened and the camera is moved to the image plane. Visible beam steering experiments are performed using a 10 mW, 532 nm laser together with a 512N15-0532 SLM and a 150 mm achromat for the Fourier transform lens. Laser trapping is performed using a 1W, 1064 nm laser together with a 512N15-1064 SLM and a 45X (0.65 NA) microscope objective for the Fourier transform lens. SF: Spatial filter. BS: beam splitter. FP: focal plane. IP: Image plane.

The digital pen is used with a custom template (Fig. 3). The template is imaged onto a special type of paper (supplied with the pen) that is required for digitizing the pen strokes. The template consists of two regions, a large writing area and a palette of variables. One starts the process by drawing a trajectory in the writing area. The trajectory can be continuous or discontinuous. Then characteristics are selected for the trajectory by drawing a dot in the appropriate boxes of the palette area. These boxes include scan velocity (first row), scan start time (second row), and the pattern that is to be scanned (third row). The process is repeated a desired number of times, each time drawing the next trajectory in the writing area and designating new parameters in the palette area. When the drawing is completed, the pen is inserted in its cradle which downloads the pen file through the USB interface to the attached personal computer. The pen data is then interpreted by a custom-written routine. Even though the pen language is capable of vector graphics, the pen only records data on a point-by-point basis. Trajectories are fit and smoothed with a β-spline [14] followed by interpolation at a rate corresponding to the selected scan velocity. The trajectory may consist of multiple distinct segments separated by gaps that exceed a pre-specified distance. In this case each segment is then separately fit, thus enabling continuous scans of a segment followed by discontinuous jumps to the start of the next segment. Actual intensity patterns produced by the SLM for the selections from the palette in Fig. 3 are shown in Fig. 4. The arrow on the fourth pattern of the spot footprint palette indicates that the pattern is a vortex beam (which has spiral phase) [15]. The other patterns are a spot, a diffractive axicon [16], a 3×3 spot array, a triangle generated using the Gerchberg-Saxton algorithm [17] and an elliptically shaped axicon.

Once the pen file is interpreted it either can be compiled for execution on the SLM, or the input parameters can be previewed and modified using the mouse-accessible parameter selection region on the Labview interface window (Fig. 5). These parameters include scaling and relative intensity of each sub-pattern. Also, the interface panel can be used to modify and

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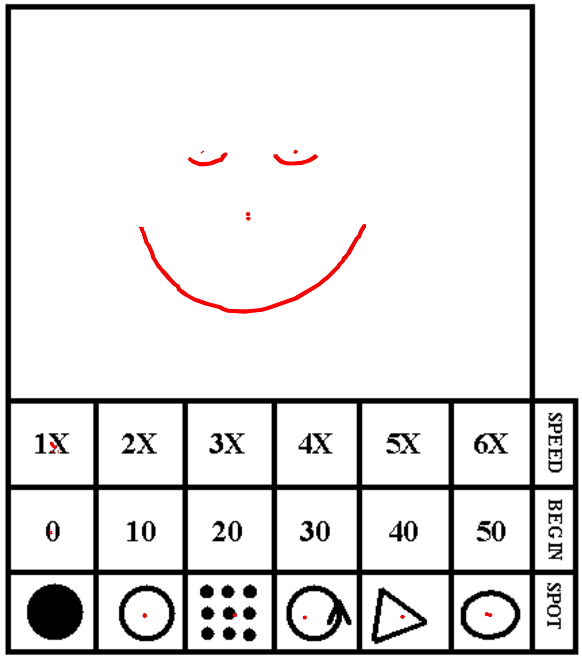

Fig. 3. The paper template that is used with the digital pen. Sketch for a beam-steering sequence is shown in red.

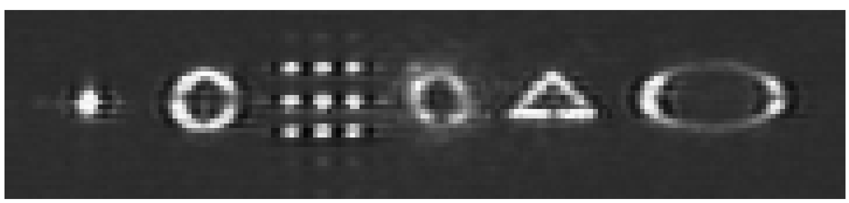

Fig. 4. Diffraction pattern from the SLM that is composed of the six patterns from the spot palette of Fig. 3. The theoretical efficiency of this diffraction pattern is 25.3%. An area of 210 x 50 resolution cells of the entire zero-order diffraction area (which is 512 x 512 resolution cells in all) is shown.

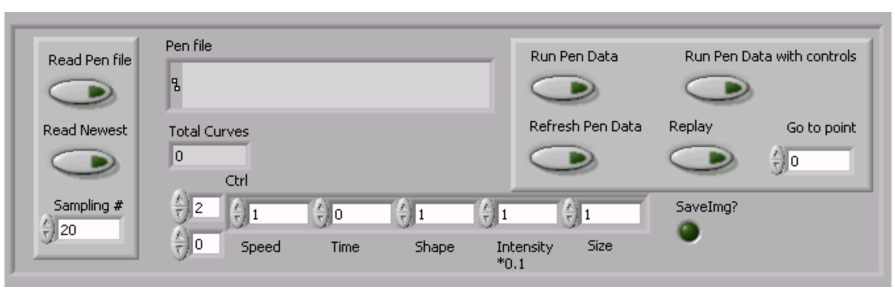

Fig. 5. Portion of the Labview control panel. Note the parameters speed, time, shape, intensity, size which can be adjusted for each spot. The parameter window with "2" indicates that the parameter values displayed are for the second spot selected from the template.

change the parameters that were originally selected from the template. Interface panel modifications are intended to be performed by engineers who develop and support the SLM system. We anticipate that interactions between casual users and SLM engineers during the

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pen input and panel modification step will suggest modifications and improvements of the template that will further improve the design of the template for the casual user.

The data extracted from the pen (and possibly modified at the interface panel) is compiled into a sequence of phase patterns using the diffractive optics design algorithms (see Fig. 1). For initial demonstrations, the current software uses fast encoding algorithms with very limited optimization of diffraction efficiency [10,11,18]. Each diffraction pattern of the sequence is calculated as a linear superposition of the user-selected spot patterns (with each pattern pre-computed in Fourier space and weighted by a complex-valued scale factor) and then the fully complex function is encoded to a phase-only modulation using the minimum distance-pseudorandom encoding (MD-PRE) algorithm [18]. (Note: MD-PRE combines the classic kinoform design [11], for modulator pixel magnitudes in excess of a threshold value, with pseudorandom encoding—PRE [10,11], for pixel magnitudes below the threshold value. The threshold is set to a value that trades-off the high diffraction efficiency of the kinoform design by using the lower efficiency PRE to reduce the highest noise sidelobes through pseudorandom diffusion. Thus the threshold is selected to maximize the ratio of desired signal intensity to the peak noise sidelobe intensity.) While improved diffraction efficiency is possible using more numerically intensive algorithms, the resulting patterns proved sufficient for the initial experimental demonstrations presented below.

The calculated phase patterns are mapped to the SLM through a look-up table that corrects both for the nonlinearity of address voltage to phase modulation and nonuniform spatial response of SLM. (The current SLM's have low spatial frequency phase variations of up to three waves over their full aperture.) The phase modulation after calibration and correction provides 25 gray levels (nearly evenly spaced) over a 2π address range of the SLM.

The current time required to generate a user-defined sequence of 100 images of 5 selected patterns through the SLM is approximately 205 seconds of which it takes 5 seconds to download, extract parameters and interpolate the pen file, and 200 seconds to generate the phase patterns (~ 0.5 frames per second) on a personal computer equipped with 2.4 GHz Pentium IV processor and 1 GB of memory running under Windows 2000 operating system. However, for encoding only one selected pattern per frame the sequence generation rate increases to ~ 10 frames per second, which indicates that most of the processing time is being taken up with repeated complex-valued additions. Much faster sequence generation should be possible given that there has been no effort at code optimization and, in fact, the current algorithms written in Labview are interpreted rather than compiled. With appropriate numeric, software and hardware optimizations it should be possible to achieve sequence generation rates that are comparable with the 30 to 150 Hz frame rate of the SLM (which is limited by liquid crystal response time rather than addressing speed) [13].

3. Demonstration of pen-generated multi-spot beam steering

We present two movies of beam steering sequences from the SLM that were specified using the digital pen. Fig. 6 shows the sequence that was compiled from the hand-drawn sketch in Fig. 3. The movie includes an animation that highlights the trajectories and indicates the spot positions simultaneously with the display of each diffraction pattern. The four stationary rings (one large circular ring, two smaller elliptical rings, and the triangular ring) were selected from the spot palette and were given a zero length trajectory. The spot directly above the triangle in the recorded diffraction patterns is on the center of the optical axis. As is typical with SLM's, the on-axis light is due to inefficiencies in the diffraction pattern design, phase errors in setting the SLM, and reflections from the cover glass of the SLM. The three non-stationary patterns are the 3x3 array of spots and two circular axicon rings. The control panel (Fig. 5) on the Labview interface was used to set the diameter for the large stationary axicon ring and to adjust the relative intensities of the various spot shapes that were selected.

The second movie (Fig. 7) shows laser trapping and manipulation of polystyrene beads (1 μm diameter, suspended in water, in a sealed microscope slide) with a second multi-spot

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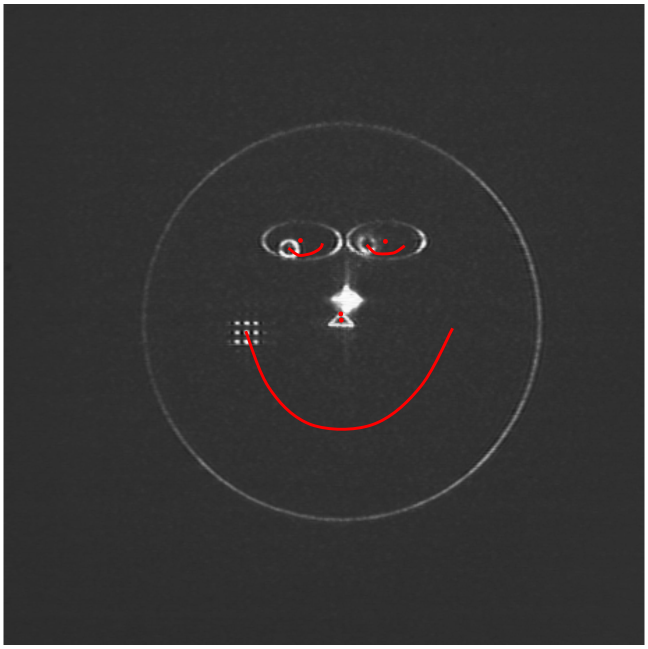

Fig. 6. (1.88 MB) The movie produced from the sketch on the template in Fig. 3. A smoothed version of the sketched trajectories are shown on top of the still image. The full zero order diffraction area is shown (512 x 512 resolution cells.) The theoretical diffraction efficiency of the multiple patterns varies from 20 to 25 %.

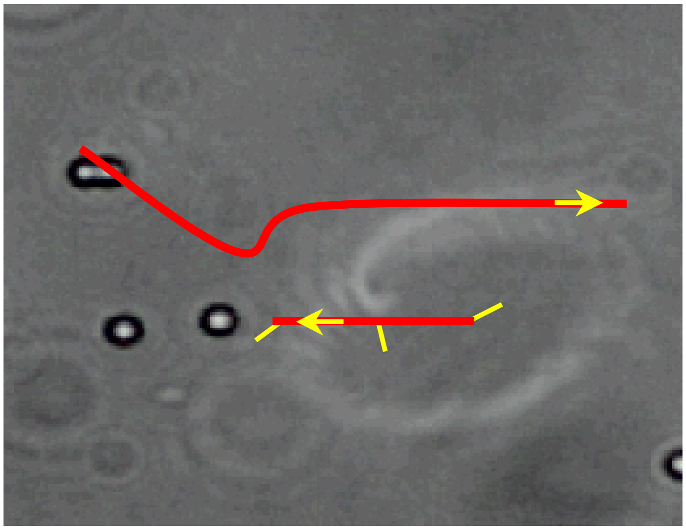

Fig. 7. (2.62 MB) Movie of laser trapping with a translating spot and a translating and rotating elliptic vortex beam. In the still image the red lines are smoothed versions of the hand drawn trajectories, yellow arrows indicate the direction of motion, and yellow lines indicate the tilt of the vortex at points along the trajectory. The movie is annotated with color highlights to indicate the position of the spots and the rotation of the vortex. On-axis light from the SLM is also evident. Note that beads from above and below the image plane come into focus as they are attracted into the beam. Optical power in the spot and the vortex totals ~16 mW during the sequence.

beam steering sequence. The optical setup is essentially identical to that in Fig. 2. The specific components used differ from the visible beamsteering system in that it uses a 1 W

1064 nm laser, a 45X microscope objective as the Fourier transform lens, a dichroic mirror for the beamsplitter, and an added hot mirror to block most of the laser light from the camera. Also there is an added illuminator from the base of a microscope that is used with the objective to form a transmission image of the beads.

As with the previous example, the spot patterns (a single focused spot and an elliptical vortex ring) are selected from the template and trajectories are hand-drawn. The trajectories are indicated in red in the still image of Fig. 7. An additional motion parameter of rotation was added to the vortex. (Rotation is controlled through the Labview interface and it is not currently a parameter specified on the template.) The movie shows that the single spot captures a bead, pulls it into the vortex ring, tries but cannot quite remove a bead from the ring and finally captures another bead at the end of the sequence. The vortex translates to the left and rotates clockwise.

Over time the vortex continues to attract and trap the beads that diffuse through Brownian motion into the vicinity of the beam. The beads also move around the ring in a counterclockwise direction due to the annular change in phase that is a distinguishing feature of vortex beams [19]. As long as the beads stay in the beam as it translates we can consider the beam motion (though actually discrete) to be comparable to the motion of a continuous scanner. Faster scanning is possible with increased laser power and trapping force on the beads. However there is substantial loss in our optics, especially from the objective which transmits only 20% of the laser power. The maximum power transmitted through to the beads is 47 mW for a single spot produced by the SLM, and the transmitted power can be even less due to less than 100% diffraction efficient designs and the limiting aperture of the objective. Note that powers in excess of 1 W have been delivered to the sample in another SLM-based optical trapping microscope [19].

4. Summary and conclusion

We have presented a simple pen-based interface for defining, with a significant degree of arbitrariness, multi-spot beam steering sequences for implementation with a SLM. The system is by no means comprehensive, but rather intended to illustrate capabilities of SLM's, with the goal of eliciting feedback and ideas from potential system engineers and end-users as to the potential applications and improvements of the beam steering system. We anticipate that even this simple interface can be used as a first step to initially establish capabilities and limitations of SLM's. Furthermore, we envision that the user interface can be adapted (through modifications of the diffractive optics design algorithms) for other electrically-addressable SLM's—not only other phase-shifting SLM's (e.g. micromechanical phase-only SLM's) but also coupled amplitude-phase (e.g. ferroelectric and twisted nematic SLM's). Using the existing interface and SLM it would even be possible, in a number of cases, to emulate the optical characteristics of these alternative devices using a combination of non-standard polarizations to illuminate the SLM, together with waveplates and polarizers to filter the reflected light.

Clearly, the performance of computer-interfaced SLM's is coupled to the control software, which can include one, or a number of diffractive optical design methods. It would be desirable to see the development of SLM-based scanning systems that serve as repositories for various successful design algorithms, and which additionally include supervisory software that automatically selects and trades-off between the design algorithms based on metrics e.g. diffraction efficiency, design accuracy, and computational time.

Ultimately, we envision the use of SLM's in unsupervised beam steering systems that automatically and continuously design and implement beam patterns in response to limited *a priori* information [1]. Laser targeting and tracking of multiple moving objects as viewed through a machine vision system is an example of such an autonomous system. Such a subsystem could support or augment intelligent robotic and other highly integrated systems. The pen-based interface, while quite limited compared to the envisioned autonomous system,

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would be an especially useful tool for introducing the system to system engineers and for more clearly defining technical requirements for autonomous multi-spot beam steering systems.

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