Multidisciplinary High Energy Laser Weapon System Student Design Study

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Abstract:

With the recent advances in materials, electric power generation and storage, and solid state laser technology, the time has come to examine the application and feasibility of developing a mobile high energy laser weapon system for the military. The high energy laser offers many advantages as a weapon system over conventional kinetic or explosive systems because of its power scalability, speed-of-light engagement capability, and precision engagement capability. The development of such a system requires the integration of numerous science and engineering disciplines as well as considerations of other factors such as the legal implications for fielding the system. Over the last two years a multidisciplinary team of undergraduate students and faculty from the United States Military Academy have been working with Lawrence Livermore National Laboratory and the High Energy Laser Joint Technology Office to help design portions of a mobile high energy laser weapon system and to examine the feasibility of fielding a system. The team consisted of physicists, mechanical engineers, electrical engineers, systems engineers, and a law student. This paper will describe the Solid State Heat Capacity Laser developed at Lawrence Livermore used in this study and identify the specific design issues addressed by the student team. It will also describe how the project was structured so that each student on the team had both an in-depth experience within their discipline and learned how to integrate their discipline specific expertise in the larger multidisciplinary project. Finally the paper will present the results of the students' work and learning outcomes.

1. Introduction

One of the desired outcomes of nearly all engineering programs is that the students participate in a project where their work is integrated into a larger multidisciplinary project. The multidisciplinary project adds more real-word constraints and considerations to the problem than a single-disciplinary project can offer. Although the students are challenged by the complexity of the problem and they are provided the opportunity to see how their particular discipline fits into a larger whole.

One of the significant challenges that nearly all multidisciplinary projects face is to balance the study in-depth of the particular discipline with the breadth of understanding required to make the project multidisciplinary. It is far too easy to break the project in such simple ways as to stovepipe the different tasks so separately that the results of one area of the project are completely independent and divorced from the rest of the work. It is also easy to make the project so shallow that there is no need for detailed analysis or work in any of the different areas. The ideal multidisciplinary project has significant study in-depth while still emphasizing the interdependence of the individual disciplines on the project as a whole.

In order to have a truly multidisciplinary project, you must first have a multidisciplinary problem. The problem addressed in this paper is based on the question of the technical and legal issues associated with fielding a high energy laser system for use by the U.S. Army. Recent advances in solid state laser designs, electrical energy generation and storage, and heat management technology have all made it possible to field a mobile laser system capable of meeting some of the challenges facing an Army deployed against the Global War on Terrorism. Add to those technologies advances in computer power for modeling and simulation, and we have the perfect situation for a multidisciplinary team of physicist, engineers, and other students to contribute to the study of the feasibility of designing, building, and fielding a high energy laser system for the Army of the future.

This paper will discuss a two year multidisciplinary high energy laser project performed at the United States Military Academy. This paper will start by describing the laser system used as the basis for the study and the specific issues addressed by the team. It will also describe how the project was structured so that each student on the team had both an in-depth experience within their discipline and learned how to integrate their discipline specific expertise in the larger multidisciplinary project. Finally the paper will present the results of the students' work and learning outcomes.

2. Project Description

For a high energy laser system to be viable for military applications there are a few desired characteristics. The first is that the lasing medium be solid state. Using a solid state laser eliminates potentially hazardous and toxic chemicals from being transported and stored on the battlefield. Another desired characteristic is that the output power of the laser be at least 100 kW with good beam quality. The power and beam quality requirements are derived from potential operational requirements of the laser system. Finally, the laser system needs be on a mobile platform. Achieving the 100 kW laser also includes managing the excessive heat generated by the laser and generating, storing, and conditioning the electric power used to run the laser. The effects of the atmosphere on the propagation of laser beam can not be ignored. It is the combination of the physics of the laser, the heat management of the system, and the electrical power requirements all developed within the systems engineering design process that makes the high energy laser a great multidisciplinary project for the students.

The laser used as the base technology for this work is the Solid State Heat Capacity Laser (SSHCL) developed by Lawrence Livermore National Laboratory.[1] The lasing medium for this laser is a neodymium-doped yttrium aluminum garnet (Nd:YAG) ceramic material. The advantage of the ceramic is that it can operate at higher temperatures than the standard crystal form. The SSHCL is also scalable in that each slab of Nd:YAG provides about 10 kW of laser output power. This makes the SSHCL convenient to analyze because you need only analyze one slab and multiply by the number of slabs.

The first year of the project the cadet team consisted of students from physics, mechanical engineering, systems engineering, and law. The second year's team consisted of cadets from physics, mechanical engineering, electrical engineering, and systems engineering. The team employed the systems engineering decision process to address the problem. The initial task for the students was to assist in the designing of a mobile solid state high energy laser system for use by the military.

Systems engineering was the driving force for the integration of work from multiple disciplines. The systems decision process ensured that the efforts of the other members of the team were focused on realistic engineering goals derived from the stakeholders affected by the system. As an example, the original problem statement from the client was to "develop a system for the military application of the SSHCL at Lawrence Livermore National Laboratories." While this problem statement clearly represents the interest of the study client, it leaves out the interests of the potential users and consumers, those who ultimately receive the value of the employed system. In fact, users and consumers could not be readily identified at the early stages of this project. Without this information, the team could not develop design objectives and requirements. A series of surveys and interviews with subject matter experts allowed the design to focus their efforts on a stand-off counter-IED system. They returned to the client with a proposal to "assist in the development of a mobile SSHCL weapon system capable of defeating IEDs, UXO (Unexploded Ordinance), and land mines." The client accepted this proposal, and the team moved on to functional decomposition and value analysis in order to further focus engineering efforts.

Based on the revised problem statement, the team decided to focus on the counter-IED function in its engineering analysis. All functional capabilities of the system were organized to support effectiveness in this mission. With the help of interview feedback, the team selected the following functions to drive engineering requirements [2].

- Operate by Soldiers- refers to the relative ease of use involved in soldiers training on this system's use
- Survive on the Battlefield- takes into account different environmental and mission aspects that would apply to the SSHCL
- Engage Target- encompasses the systems involved in powering, shooting, and cooling the laser
- Move- refers to the mobility and maneuverability of the vehicle platform
- Legal- relative compliance with international law

These functions led to objectives and ultimately weighted performance measures that could be used to assess the relative value of different design alternatives. Figure 1 shows the results of this process for the "Engage Target" function.

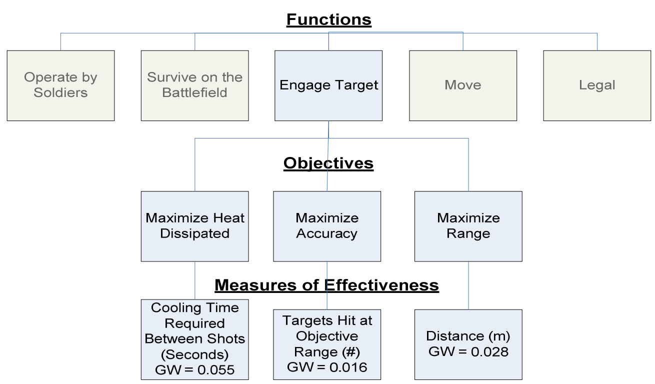

Figure 1. Functional and value analysis for SSHCL.

Given the objectives and measures of effectiveness from the value analysis, the design team was able to enter a values-based creative effort to develop design alternatives that achieved the stated objectives. These objectives and values further focused the team through development of screening criteria to rule out infeasible designs and scoring criteria to assess design trade-offs.

During the first year of the study, the physicists studied the beam propagation through the atmosphere and the lethality effects of the laser on potential targets to determine the minimum laser output power required to be effective. He used the tactical scenario developed by the systems engineer as input parameters to the High Energy Laser End to End Operational Simulation (HELEEOS) laser propagation model developed at the Air Force Institute of Technology. The study included varying laser and scenario parameters such as beam quality, output power, target thickness, weather conditions, target range, and engagement time to determine the probability of deflagrating the IED. The goal was a probability of kill of 90%. Figure 2 demonstrates the effect of weather on the fluence on the target as a function of the output power of the laser. The damage susceptibility line depicts the fluence required to deflagrate a typical IED.[3] The results of the physics modeling and simulation were fed back to the mechanical engineer to drive the heat management requirements and provided to the systems engineer for input to the systems engineering design process and functional analysis.

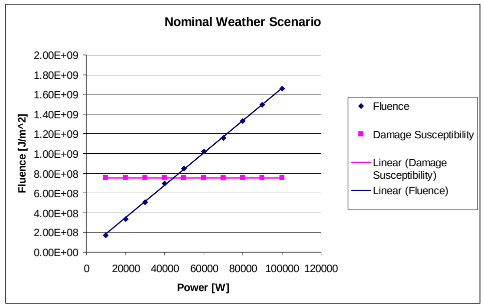

Figure 2: Fluence on target for a given laser output power for a nominal day in the area of interest.

The mechanical engineer developed a heat management system for both the lasing medium and the pump diodes. He took the required laser output power from the physicists and constraints of the system, to develop a heat management solution. He provided the systems engineer the size and weight of the heat management system for integration into the vehicle.

There were several heat related constraints on the system that the mechanical engineer had to balance. The first of these was managing the temperature of the laser diode bank that pumped the lasing medium. The diode bank needed to maintain a 14^{o} C equilibrium temperature so that the diode bank most efficiently coupled the pump energy into the lasing medium. The solution included using the microchannel phase change heat exchange system. The work resulted in the determination of the type of refrigerant, the size of the microchannels, the flow rate for the coolant, and the size of the coolant system.

After developing a potential solution for managing the excess heat from the pump diodes, the mechanical engineer turned his attention to managing the excess heat generated by the lasing slabs. If the slabs get too hot they can crack and fail. It is also important that the slabs maintain a homogeneous temperature across the face of the slab to maintain the quality of the laser beam. The team at Lawrence Livermore had already done a significant amount of work in this area and had a developed a rotating heat exchanger. The rotating heat exchanger consisted of several lasing slabs mounted in a circular structure that rotated slabs into the beam like the cylinder of a revolver. The slabs not in the beam line would be cooled by convention plates. The challenge was to determine how close the convection plates needed to be to slabs, how much heat the convection plates needed to dissipate over time, and how big this system would be. A finite element analysis model was developed for the cooling plates and Nd:YAG lasing slabs to predict the temperature of the slabs over time and derive the heat management system requirements (Figure 3).[4] These requirements were then fed back into the systems engineering design process.

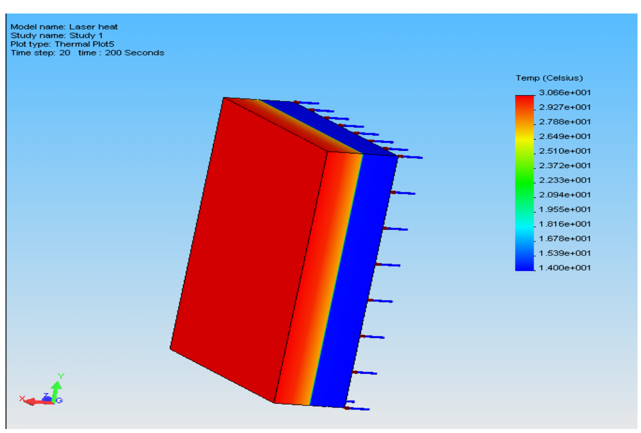

Figure 3. COSMOS finite element analysis of the heating of the ceramic lasing slabs.

The law cadet provided an in-depth analysis of the law of armed conflict and the impacts those laws and treaties would have on the fielding of a high energy laser system. He was included in the project to demonstrate to the engineers that there are factors outside of strict engineering solutions that must be considered when designing real equipment for real people. The most significant constraint discovered during the legal review is the prohibition against developing a laser weapon system whose primary purpose is to blind. The blinding of combatants and non-combatants places an unbalanced burden on the society compared to weapons designed to kill. Based on the legal analysis, he found that there were hardware and software solutions that should be added to the system to make its operation more legal. Some of the engineering solutions included moving to more eye safe wavelengths for the laser, including a power control mechanism so that the laser emits the minimum power required to accomplish the mission, and developing a system that allows the operator to know if any off-axis reflected light becomes blinding to those in the area.[5] These solutions were fed back to the engineering teams for integration into the system as a whole.

Once the engineers on this project completed their component designs, systems decision process supported assessment of the relative value of these designs in order to make a recommendation to the client. Figure 4 shows the results of this analysis for each of the design alternatives.

			20 kW	40 kW	60 kW	80 kW	100 kW
Objective	**Weight**	**Ideal**	**HMMWV**	**Stryker**	**M113**	**Cougar**	**Cougar**
Min. Personnel Req.	0.132	2	100	88	88	88	88
Max. Resistance	0.086	38 mm	20	38	100	20	20
Min. Exposure Time	0.06	2	13	50	88	88	100
Max. Heat Dissipated	0.055	0 sec	100	75	80	50	20
Min. Size	0.053	HMMWV	100	34	71	87	87
Min. Weigh	0.053	HMMWV	100	32	60	59	59
Max. Maneuverability	0.03	125 km/h	100	80	53	84	84
Max. Vehicle Range	0.015	600 km	46	52	50	100	100
			27.751	**23.464**	**37.205**	**27.712**	**26.812**

Figure 4. Values-based scoring of design alternatives for SSHCL.

Based on this analysis, the design team recommended a 30kw design on an M113 chassis. This chassis allowed for a small crew size and high survivability while being large enough to support the associated cooling and power systems. The 30kw laser still had sufficient power to destroy an IED in 3 seconds.[2]

The second year of the project followed a similar path to first but the problem the team addressed was a bit more broad. The team consisted of a system engineer, physicists, mechanical engineer and an electrical engineer. The broadly stated problem was to determine if a high energy laser weapon system is a viable replacement for the conventional kinetic systems of today. Again the systems engineer took the lead in refining the problem statement and working through the stakeholder analysis. The team roughly outlined five tactical scenarios that included the counter rocket artillery and mortar missions, counter IED mission, and anti-aircraft mission, and anti vehicle mission and an anti-personnel mission. As in the first year of the study, the cadets were required to identify their discipline specific goals and objectives and state how there work was supported the overall team goals and objectives and how their results were connected to the others in the team.

The systems engineer is leading the development of the tactical scenarios and determining measures of effectiveness for the system in each of the scenarios. Some of the measures of effectiveness include the number of in-coming rounds destroyed divided by the number of rounds fired, the number of

IEDs safely destroyed divided by the number of IEDs detected. He is in the process of setting-up the framework for comparing the performance of the current kinetic systems to that of the high energy laser systems.

During the second year of the project the mechanical engineering cadet shifted focus away from a particular laser system and instead examined the heat transfer from the laser beam to the metallic target. The mechanical engineer received beam characteristics and potential power ranges from the physicists. He then developed a model that characterizes the heat absorption of the metal target. The model terminates when the metal begins to become a liquid. The model also monitors the temperature on the backside of the metal target. When the inside of the casing of an artillery or rocket round gets hot enough, the explosive inside detonates causing premature deflagration. The time it takes for the metal to begin to melt or the round to deflagrate is fed back to the physicists to confirm their modeling efforts. It is also provided to the system engineer for input to the measures of effectiveness and fed to the electric engineer to drive electrical power generation and storage requirements.

During the second year the physics majors are looking more closely at the trade offs between laser output power and the beam quality. The lower the beam the quality, the larger the laser spot is at the target and smaller the energy per area on target. The team is also examining the effectiveness of a pulsed laser versus a continuous wave laser. The team is again using the HELEEOS modeling program to vary the output power of the laser and the beam quality to get the time on target for a probability of kill at 90% or better. These parameters are compared to the mechanical engineer's heat transfer model and fed to the electrical engineer for consideration of the electrical energy generation and storage. The systems engineering is including the information in his assessment of the measures of effectiveness.

A cadet majoring in electrical engineering joined the project in the second year and was asked to focus on the electrical energy generation and storage challenges associated with a practical laser system. This required the student to work in collaboration with the other team members as tactical scenarios and conditions under which the laser system would operate were identified and defined. For the electrical engineer, the required laser beam power was the driving specification for the electrical system.

From a military application or tactical perspective, as one would expect, as the beam power requirement increases, the energy storage and generation requirements also increase. This results in a corresponding increase in the physical footprint of the laser system and an increase in the necessary logistical support required to sustain the system in a tactical environment. Through this analysis, it became clear that there was a feasible limit to the beam power that would make the employment and sustainment of a laser system in a tactical environment practical.

With the challenges identified and the design trade-offs of a practical laser system understood, the electrical engineer used access to the LLNL and Textron systems as a benchmark for a state-of-the-art system. Through direct interaction with LLNL and Textron engineers, the electrical engineering team member identified the requirements and methods being used for energy generation and storage in these developmental systems. This led the cadet to determine that a lithium ion battery storage system was the storage system feasible at this time. He also identified the fact that the developmental systems were all either using laboratory wall-plug power with an expectation of using existing diesel tactical generators to generate power for the system once deployed.

Through the analysis of the existing systems, the electrical engineer was able to identify that the key design parameters for the electrical storage system were energy and power density. Figure 5 shows a plot of the battery mass and size as a function of the stored energy power based on energy density and energy storage specifications for state-of-the-art lithium ion battery technology. The computation assumes a system power efficiency of 10% requiring the system to be able to store energy a minimum of

10 times the HEL beam power. By comparing the size and weight requirements of a power storage system to the size and weight capacities of current fielded cargo systems, the electrical engineer was able to confirm feasibility of producing a HEL system in a footprint similar to the size of other tactical systems.

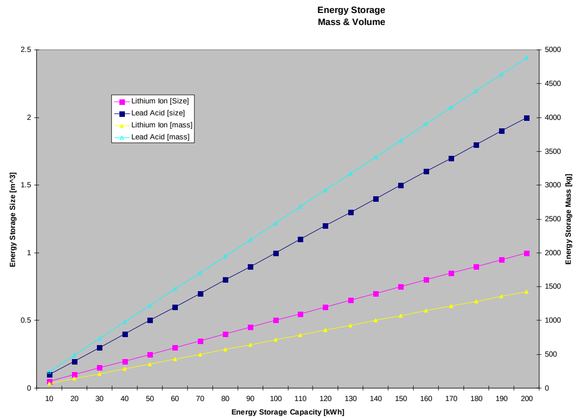

Figure 5. The physical size and mass of a two battery systems is compared as a function of the required HEL system capacity.   The data was calculated using energy density and power density specifications for various energy storage systems.

The footprint of the electrical energy generation and storage is provided to the systems engineer for input to feasibility model for a system. Constraints on the system are also generated and shared with the rest of the team.

3. Learning Outcomes

From a technical perspective, the interaction between team members served to familiarize each cadet with the critical concerns of the other disciplines. The high energy laser served as an excellent vehicle to meld the expertise of several science and engineering disciplines as well as a non-engineering discipline. Critical to making this project a success in terms of providing the ability to conduct a study in-depth and exploit the interdependence of the different disciplines was properly defining the problem. The requirement for each member of the team to identify their particular supporting tasks for the team mission and to identify the inputs to the other team members prevented the project from becoming stove piped. This process also enabled all student to see the trade-offs analysis that is associated with most multidisciplinary problem.

Through the multidisciplinary project, the cadets were exposed to challenges associated with system design. As one team member changed one single variable, the effect reached all systems. Constant dialogue and coordination was required to provide a consistent analysis of the project. For example, through trial and error the cadets learned that if the electrical engineer analyzed the system entirely using a 20 second duty cycle yet the physicist did not provide data for beam power requirements for this cycle, results and conclusions were difficult state. The laser project illustrated the need for a broad understanding of the engineering and science disciplines with in depth knowledge in individual areas of expertise. The inclusion of the legal analysis of the laser system demonstrated that development of a complex system can not ignore human and social factors on optimizing a solution.

Although many of the conclusions and results of the cadets' effort were not revolutionary, they did provide the high energy laser community a fresh perspective on the problem of developing and fielding a high energy laser system for military applications. The cadets challenged many assumptions and increased the dialogue amongst several diverse members of the high energy laser community.

Probably the most significant outcome of this project was that the cadets and faculty involoved in this work were forced to become conversant in fields outside their own. They were all required to learn the basics of lasers operation and beam propagation, heat management, the systems engineering design process, electrical energy generation and storage, and the law of armed conflict as applied to weapons development. This exposure supports the education mission and instills confidence in the cadets as to their ability to select a subject, learn on their own, and apply what they have learned to new and challenging situations.

4. Acknowledgement

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