An Examination of Laser-Based Guidance Systems and Relevant Applications

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

Since their introduction by Dr. Theodore H. Maiman at the Hughes Research laboratories, lasers have captured the interest of the public and the scientific community. In the August 6, 1960 landmark publication in *Nature*, "Stimulated Optical Radiation in Ruby", Maiman describes the experiment in which he utilizes a "high-power flash lamp" to induce a high-power excitation to a chromium-in-corundum ruby crystal "of 1-cm. dimensions coated on two parallel faces with silver", producing "stimulated optical emission" (Maiman, 1960b, p.493-494). This was the culmination of less than a year of experimentation, including experiments that proved the emission of light from a ruby crystal and examined other optical properties of ruby, observing "ground-state population changes…due to optical excitation and the detection of optical absorption between two excited states (Maiman, 1960a, p.565). This experimental setup was small enough to fit in the palm of a hand, "a cylinder-shaped crystal about 1cm in diameter and 2cm in length…[with] two opposing surfaces polished flat, parallel to each other, and normal to the axis of the rod" (Rawicz & Holonyak, 2014, p.6-7). Maiman's laser needed 500 volts to detect fluorescence, while modern laser modules, much smaller in size, operate on voltages in the single-digit range, producing highly visible beams (Quarton Inc., 2021). Over the past sixty years, laser research has evolved from its origins in maser research to become its own distinct and established field; as the technology continues to progress, its capacity for both advancing human endeavors and inflicting significant harm has become increasingly evident. I consider both aspects by presenting case examples of applications of lasers to guidance systems, developing a better understanding of the interconnections of laser technology and ethical design.

Background

In this paper, I explore several case studies of laser applications in guidance systems, investigating the ethical implications of the technologies developed in each case. The development of laser technology begins in the mid-20th century. By 1958, scientists were already hypothesizing applications of the maser (microwave amplification by stimulated emission of radiation) to "the infrared and optical region": one such paper, by Arthur L. Schawlow and Charles H. Townes, discusses theoretical "aspects of maser-like devices for wavelengths considerably shorter than one centimeter", seeking to induce an excitation using a high-power light source with a hypothetical use of sapphire, a material that has "good chemical inertness and excellent infrared transmission" (Schawlow & Townes, 1958, p.1948). This purely theoretical optical maser would be the foundation for Maiman's own research and development, which would become the laser (light amplification by stimulated emission of radiation). Stimulated emission occurs with interactions between electrons and some energy source. From quantum principles of atomic absorption and the radiation of photons, when some electrical current or light induces an excitation, this can push electrons to a higher-energy orbital: the inducement of additional energy to move those electrons back to their ground state then causes the emission of photons (Lawrence Livermore National Laboratory). This is the foundation of laser operation. A laser device is comprised of an optical gain medium, such as solid-state materials like ruby crystal or gases like CO_2, ensuring coherent light waves in that "the beam of photons is moving in the same direction at the same wavelength" (Ibid.). Mirrors within the device reflect photons towards electrons located in the cavity to stimulate photon emission, until the number of photons generated within the cavity causes them to pass through the mirrors in unison and emit a beam of a singular wavelength. Maiman's original ruby crystal laser is an example of a solid-state laser, where the optical medium is a high-purity crystal with some degree of doping from another element: the ruby crystal was a sapphire Al_2O_3 crystal doped with chromium Cr^{3+} ions: the actual lasing occurs between "electron energy levels of the dopant embedded in the solid". Modern laser devices utilize a variety of optical media, including dye lasers, where the material is a solute submerged in liquid; gas lasers, constructed using a gas-filled glass tube; or semiconductor lasers, where the construction is like that of diodes or LEDs, in which the wavelength is dependent on the semiconductor energy gap (Mitofsky, 2018).

Applications

Considering the extensive technical groundwork, what are the practical applications of lasers? Many devices incorporate semiconductor lasers, also known as laser diodes, such as scanners, printers, pointers, and barcode readers due to their compact size, enabling versatile deployment. In 1960, the scientific community faced the task of demonstrating the broader potential of this innovative technology compared to its predecessor, the maser. Charles H. Townes, one of the leading minds in masers and one of the winners of the 1964 Nobel Prize in Physics for his "fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle" (Nobel Prize Outreach AB 2024), mentions in his retrospective on the laser that it was "a solution looking for a problem" (Lincoln et al, 2003, p.107), and that the popular conscience almost immediately latched onto "front-page newspaper discussions of possible death rays" (Ibid., p.108). In the past sixty years, lasers have found applications in various fields such as medicine, fiber-optic communication, astronomical observation, and office supplies, although their portrayal in popular culture frequently takes precedence over these practical uses.

The concept of a directed-energy weapon is not new: the first reference in popular culture to such a weapon comes from H.G. Wells' 1898 novel *The War of the Worlds*, where he mentions "an intense heat in a chamber of practically absolute non-conductivity…project[ed] in a parallel beam against any object they choose, by means of a polished parabolic mirror" (Wells, 1898), utilized by Martians to terrorize a helpless human populace. Popular science fiction has continued to explore the laser as a weapon, in films like the James Bond film *Goldfinger* (1964) as a death-trap device, which premiered only four years after Maiman's publication in *Nature*; or the *Star Wars* franchise, where hard-light weapons known as lightsabers as well as laser-based firearms abound. One of the most prominent depiction of lasers in popular media may in fact be the sinister Death Star and its successors, devices with planetary-scale destructive abilities (Warren, 2020).

Directed-energy weapons remain a very real possibility. During the peak of U.S.-Soviet tensions in the 1980s, President Ronald Reagan's Strategic Defense Initiative, fittingly nicknamed "Star Wars," investigated the potential use of ground- or space-based lasers to counter intercontinental ballistic missiles (ICBMs) (Yonas, 1985). Military forces also use lasers as sights to assist the aiming and targeting of other weapons, a secondary implement that may perhaps be an "accomplice" to political acts, as well as target designators to enhance the accuracy of precision-guided munitions (e.g., missiles and other rocket-propelled projectiles or explosive devices). This paper will delve deeper into some of these military applications.

Additionally, even those uses not militarily applicable encounter safety issues in user interaction, most prominently in terms of the use of laser pointers or commercial laser devices with relation to aviation safety. The United States Federal Aviation Administration notes that 9,457 laser reported incidents in the year 2022, posing "a safety threat to pilots", in that "many high-powered lasers can incapacitate pilots flying aircraft that may be carrying hundreds of passengers” (Federal Aviation Administration, 2023). Therefore, it becomes imperative to thoroughly consider the safety, ethics, and technical viability for any invention or device incorporating lasers. This paper explores these cases to provide a comprehensive analysis of laser technology's applications in guidance and navigation systems, utilizing an ethical perspective to better understand their sociotechnical impacts.

Methods & Frameworks

To explore the technical background and social contexts of laser system design and development, I conducted an extensive literature review, examining government reports, technical documentation, and research literature, organized in three stages. Firstly, I explored the technical foundations of laser technology, spanning from Theodore Maiman's conception at Bell Laboratories to the current solid-state laser, covering over sixty years of development. This approach facilitated an understanding of the technology's historical progression. The second stage involved analyzing non-technical societal contexts by comparing timelines of key development points in laser technology with major political or economic factors. This comparison provided insight into the motivations for technical development beyond a strictly scientific perspective. Finally, I examined policy frameworks and current applications of laser technology to consider future innovations, including mobile robotic guidance, military directed energy weapons, astronomical telescopes, laser microscopy, and others. By following these stages, I gained a comprehensive understanding of the evolution of laser technology, compared its popular and scientific perceptions, and evaluated the ethical implications of its use.

For this project, I used Actor-Network Theory (ANT) to trace the technical development and history of lasers along with their systemic sociotechnical impacts, and to observe a clear cause-and-effect progression within a narrative context. An ANT approach complements the subject matter: examining the intersections across disciplinary boundaries with ethics in engineering design allowed me to both deconstruct and reconstruct “solid reality as the outcome of an organized, fragile, and laborious process of material articulation” (Muniesa, 2015, p.80). Using this approach, I was able to reconcile the “social” science of studies in ethics and the “harder” science of laser engineering to develop a more overarching but not comprehensive discussion. In this context, Bruno Latour, one of the principal developers of the theory, clarifies that it is not only the typical technical definition of a network, and may even lack those traditional characteristics, in that it “may be local, …have no compulsory paths, no strategically positioned nodes”; that it includes not only human individual actors, but also “non-human, non-individual entities” (Latour, 1996). This ultimately involves analyzing researchers, governmental bodies, policing organizations, and users, alongside laser devices and systems themselves.

I examined three key questions to develop a comprehensive understanding of laser technology and the ethical implications of the interconnections between the nonhuman actors and the agency of both designers and users in shaping applications. Firstly, I investigated the current state-of-the-art in laser technology and its potential risks to establish a technical foundation and identify relevant actors (i.e. designer and design, product, and user). This inquiry helped delineate the concept of "harm" in laser technology, considering its diverse applications. This also allowed me to consider actor effects within subnetworks, their cross-connections, and the overall network. Secondly, I explored existing frameworks or initiatives aimed at mitigating harm to provide a basis for analyzing case studies and to solidify actor definitions. Finally, I assessed the current state of ethics, policy, and technical development to envision the future of laser technology and identify potential proactive measures. While I refrain from making policy recommendations, my analysis maps the ANT framework onto the engineering design process, to offer insights into proactive design strategies.

Conducting a thorough analysis and synthesis of the literature, I integrated it with the ANT framework to enhance the understanding of historical and technical developments and their impact on design. Utilizing a case-study approach enabled the extraction of conceptual insights and ethical implications from specific examples, facilitating a broader synthesis for a comprehensive perspective. This approach facilitated cross-comparison between cases with similar conclusions or contexts, addressing my three key questions.

Results & Analysis

Military and Defense

The most prominent depiction of lasers being in its utility in military applications, it seems fitting to examine such cases first. In 1980, the Guidance System Evaluation Laboratory (GSEL) at the Johns Hopkins Applied Physics Laboratory (APL) examined how surface-to-air missiles may be designed to “home passively on radio frequency (RF) energy” from a target, utilizing processing techniques to distinguish between interference and the energy of the target, such as “amplitude, frequency, coherency, and angle-of-arrival measurements”, evaluating guidance systems based on their ability to select “the best available signal to derive steering information” (Gray & Witte, 1980, p.144).

The United States military has used laser-guided explosive devices since 1968, relying on target illumination to home on their target: “the target is lit up by a laser spot of distinct wavelength and modulation. A detector inside the bomb identifies this signal, and using control flaps, the bomb is automatically guided to the designated target” (Stupl & Neuneck, 2005, p.137). One civilian technology with military origins is LiDAR/LaDAR, or Light/Laser Detection and Ranging: used in civilian cases for laser-based range-finding, such as seafloor mapping, agricultural surveying, or even archaeology in sensitive or fragile areas, the military has used LiDAR to generate “three-dimensional maps for cruise missiles navigation using a generalized method of range-finding”, including “detection of chemical warfare agents within the atmosphere” (Ibid. p.137). Furthermore, the Reagan-era Strategic Defense Initiative (SDI) aimed to shield the United States from potential nuclear attacks by the Soviet Union during a period of heightened political tensions between the superpowers. Immediate global outcry from the televised announcement in 1983 included such concerns as an undermining of the “American and Soviet deterrence policy of mutually assured destruction (MAD)" (Atomic Heritage Foundation, 2018), where mutual fears of total nuclear annihilation maintained an unstable equilibrium state. The introduction of SDI threatened the delicate balance reinforced by the 1972 Anti-Ballistic Missile Treaty between the Nixon and Brezhnev administrations. Political opponents and the scientific community raised doubts about the feasibility of SDI meeting the ambitious goals set by the Reagan administration. In terms of international response, United States allies brought up fears of SDI being a "backing away from this commitment to Europe and building a 'Fortress America', with this high-tech system that would protect us, but not them", according to U.S. Ambassador to Canada Thomas Niles (Atomic Heritage Foundation, 2018). The implications are evident: to the United States' allies, SDI signaled an isolationist stance, an "America First" approach to international diplomacy, and a precipitous threat to the balance among global nuclear powers. In the military context and global political climate of 1983, understanding laser technology involves defining "harm" as the potential for mutual assured destruction (MAD), resulting in the total annihilation of the populations of the U.S. and Soviet superpowers due to the threat of nuclear war. Another question arises: is the potential to initiate such a fate too much power to grant to any singular individual?

In the network of SDI, the Reagan administration was the driving actor in maintaining the structural integrity of the project, in opposition to both foreign and domestic detractors in political and scientific spheres. From a political perspective, timing a major defense project for 1983 would contribute to controlling the political narrative in an election season where Reagan's approval rating had reached its lowest. Harnessing both anti-communist and anti-Soviet sentiments from the public gave the administration the public support backing it needed to push for such a major project. Ultimately, by 1993, two administration changes (not to mention a change in the political party in power), continued scientific disproval of feasibility, and the collapse of the Soviet Union had significantly decreased interest in the project, and with the unifying force of the Reagan administration's zeal for SDI having faded, SDI ultimately dissolved, with its elements redistributed to other sectors.

Even in the current day, the Air Force Research Laboratory (AFRL) is conducting its own research and development into laser-based anti-drone weaponry. The Tactical High-power Operational Responder (THOR) in its testing phase is being used as a "high-power microwave counter drone weapon", to counter swarms of drones using "its wide beam, high peak powers and fast-moving gimbal to track and disable the targets" (Rogers, 2023). As military technology advances, it prompts reflection on the nationalistic approach to defense and the competitive arms race against rival nations, as described by Reagan's rhetoric of "evil empire" states. To what extent are lessons from history assimilated into future design deliberations? Although not at the level Reagan envisioned in 1983, the prospect of a "Star Wars 2.0" is already feasible: in 2021, the Israeli "Iron Dome" defense system began incorporating a high-powered laser system to use against missiles from Hamas or Hezbollah, prioritizing eradication of "attacks from the air – by missiles, drones, fire balloons, and even kites" (Strauss, 2021). This serves as a prime example of harmful actor utilization of laser technology, defining harm as the continued Israeli occupation of Palestinian territory since 1948 and the settler state's oppression and displacement of the Palestinian people. The usage of this technology may even prolong or exacerbate the inhospitable present situation in Palestine. Considering oppressive occupations, does the benefit of technology development for national defense worldwide outweigh the harm to the Palestinian people? Israel has killed more than 30,000 Palestinians through their genocidal campaign, and thousands more die each day from starvation and sickness (Global Centre for the Responsibility to Protect, 2023). What responsibilities do influential global entities like the United States, NATO, and the European Union bear?

Navigation Systems

Similarly to laser-guided missile systems, laser technology also upgrades vehicles with automated navigation systems, essentially like more sophisticated versions of line-following robots: with the flexibility provided of distance-measurement from ranged laser scanning, laser-guided vehicles (LGVs) can “move through a facility on multiple paths and the paths can change as needed” (Banker, 2018). One such implementation, as detailed in Steve Banker’s *Forbes* article about precise laser navigation, a facility might mount laser sensors to the automated vehicle, and post reflective strips of tape along a given path that they might want the vehicle to follow. These “rotating laser sensors…receive the reflected signals and use that data to triangulate the vehicle’s position” (Ibid.). The technology's advantage lies in automated path-following, enhancing efficiency and vehicle navigation. Beyond industrial settings like warehouses, where it assists in pallet transportation and navigation within large facilities, it could extend to flexible pathing for automated transport vehicles, potentially ferrying passengers. However, prominent economic concerns arise. One dominant consequence is that automation often leads to higher unemployment as machinery replaces human workers. Companies may opt for downsizing rather than investing in employee training, prioritizing profit maximization, an example of the classic employer-employee dichotomy, with employers balancing the costs of human labor against those of machines. Additionally, system reliability concerns include the risk of vehicle deviation due to sensor failures or unforeseen programming errors, requiring preemptive measures to mitigate potential physical or financial harm resulting from these failures.

Another navigation-based application of lasers is their use for altimetry for spacecraft landers, an extension of the previously mentioned LiDAR/LaDAR systems, utilizing the same principles to achieve accurate vertical positioning:

> A pulse of laser energy is emitted, it reflects off a target surface, and a receiver detects the reflected energy. The time between pulse emission (start) and pulse reception (stop) provides a measure of the target distance, or range…based on the speed of light…Detection methods of varying complexity can be used to reveal characteristics of the target in addition to range, such as reflectance and toughness in the case of a hard target or, with additional analysis, chemical makeup in the case of an aerosol target, for example (Bruzzi et al., 2012, p.332-333).

Spacecraft landing precision is a prominent application of laser altimetry. Laser guidance systems provide accurate distance measurements between the module and the surface, facilitated by a focused beam. Multiple lasers enable interpolation of the module's position in three dimensions. Given the technical and financial risks of space exploration, rigorous pre-launch testing is imperative to avoid errors or catastrophic failure. Engineers must balance ruggedness and versatility with instrumental accuracy, considering mission goals and experimental objectives. However, client decisions contrary to expert advice or oversight of test procedures can undermine these efforts. Handily enough, recent events present such an example. At time of writing, the IM-1 *Odysseus* lunar lander, the first U.S. lander since the end of the Apollo program in 1972, prematurely ended its mission after a landing gone awry. While it is surely remarkable that “Houston-based Intuitive Machines became the first private business to land a spacecraft on the moon without crashing when *Odysseus* touched down Feb. 22” (Dunn, 2024), the circumstances of that landing demonstrate some expensive consequences. Several systems were determined to be missing or not in use:

> A safety switch that would have activated the spacecraft's laser landing navigation system was left on 'off'. When the flight engineers discovered this following launch, they found a workaround, using a software patch to allow NASA's Navigation Doppler Lidar experiment aboard the lander, commandeering the inactivated system. However, a data flag was missed – one that would have allowed the software to determine if data was valid. *Odysseus* was largely flying blind and relying on its inertial guidance system and optical navigation algorithms. This meant that the lander didn't have an altimeter to tell it how high it was as it descended to the lunar surface (Szondy, 2024).

Without equipment accurately feeding information about *Odysseus*'s vertical position relative to the surface of the Moon, the lander broke one of its six landing legs, and tipped "over near the lunar south pole", ending up "on its side with hobbled solar power and communication" (Dunn, 2024) because of its sideways position, presenting a tangible network failure. Examining the interests of Intuitive Machines executives and stakeholders in seeing the launch carried out, two goals presented themselves: first, a monetary return on investments made in the private space venture, and second, greater publicity and attention to Intuitive Machines brought by a nominally-successful mission. With this pressure on the joint development team between the private corporation and NASA, as well as the ever-present pressure from the U.S. government to justify funding for space research, the push to go forward with the launch was a significant factor. These client interests ultimately led to the oversight of the testing and pre-launch procedures that would have otherwise contributed to better chances of success.

Such an instance presents "harm by omission", where neglectful actions prior to launch, though unintended, result in adverse outcomes. Beyond immediate impacts like the sideways landing or premature mission termination due to low power, broader considerations arise. Scientifically, with six NASA experiments on board, the immediate concern would be the risk of compromised data due to the rough landing. While NASA designs space experiments to withstand harsh conditions, their resilience has limitations, with experimental conditions being a significant factor.

Additional political and economic impacts present themselves: the mission, which “received $118 million in funding from NASA to build the lunar lander and transport experiments” (Zhou, 2024) may end up labeled more charitably as an unfortunate failure, or more antagonistically as a colossal waste of time and money. NASA, often tasked with justifying its budget and existence, may face challenges as detractors seize upon incidents such as this to advocate for redirecting funding from space exploration. Additionally, private spaceflight introduces risks related to conflicts of interest among public officials, lobbyists, and private entities. There is an anecdotal phrase that says that “laws are written in blood”: In the future, as space travel becomes more commonplace, regulation akin to the United States' Federal Aviation Administration (FAA) will be essential to prevent human casualties or disasters beyond company policies. Global airspace sharing is already contentious due to geopolitical territorial claims and diplomatic relations. The competition between nations for territory and scientific advancements in space exploration brings similar expected challenges. With a space race under way as the United States’ Artemis Project competes with rival lunar projects like China’s Chang’e Project or India’s Chandrayaan program, the “urgency behind…establishing a presence on the moon” (Zhou, 2024) brings a variety of challenges to all parties. The case of *Odysseus* highlights the pivotal role of the laser altimetry system in mission outcomes and the potential cascading issues that could present themselves in future spacecraft incidents.

Discussion & Conclusion

Synthesis

After examining various examples across laser technology applications, the potential for harm becomes evident. While it may be tempting to dismiss issues in these case studies as having straightforward solutions—both technically and socially, politically, or economically—practical resolutions are not as readily apparent. For instance, the Strategic Defense Initiative demonstrates that certain military applications carry wide-ranging geopolitical consequences, affecting adversaries and allies alike. Similarly, Israel's utilization of laser technology in its ongoing occupation of Palestine highlights significant cascading effects, as establishing a foundation for further technological development may prompt other entities to employ similar technologies for harmful purposes under the guise of defense. The politics and economic implications of laser application in space exploration further underscore the complex nature of these considerations. Ultimately, the issue is in balancing the desire for technical and scientific advancement with the need to operate within the contexts of the society engineers invent for.

However, there is an element of intersectionality in the technical design process. Technologies intertwine with their contexts, and one inevitably affects the other. In his 1980 piece in *Daedalus*, Langdon Winner asks the pivotal question of "do artifacts have politics?" In the case of lasers, there is not a definitive answer. Lasers themselves, light amplification by stimulated emission of radiation, may not have an inherently political nature in the same way the atomic bomb might, where "its lethal properties demand that it be controlled by a centralized, rigidly hierarchical chain of command closed to all influences that might make its workings unpredictable" (Winner, 1980, p.131), but by nature of the public perception (through popular science fiction media), or by precedent through current utilities, there exists an inherently political element of laser-*based* technologies.

Concluding Thoughts

Charles H. Townes says of Theodore Maiman's first publication that it "is so short, and has so many powerful ramifications, that I believe it might be considered the most important per word of any of the wonderful papers in *Nature* over the past century" (Lincoln et al. 2003, p.111). Certainly, modern lasers find applications across nearly every scientific discipline, offering boundless potential for future development and innovation. Consequently, it becomes imperative to contemplate the ethical implications inherent in this advancement process: what does ethical design entail for a technology so prone to usage as weaponry? In an era marked by increased technological interconnectedness juxtaposed with heightened societal isolation, what defines ethical progress and innovation? Such questions prompt speculation. The risk of technology misuse necessitates consideration from policymakers, corporations, ethicists, and engineering designers alike. By extension, the potential for resulting harm or its precursory effects demands attention. In a world asking engineers to design for good, the ethical considerations designers make in the present will shape the future they choose to create through technical design and. With mindful and innovative scientists and engineers at the helm, a technology as potent as the laser holds promise for a bright and luminous future, guiding humanity towards new horizons.

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