On the State of Sensors

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The field of robotics is built on the capabilities of sensors which measure signals from the physical world. Therefore, we can see that there are two exciting frontiers which demand the invention and utilization of new technology: sensors to gather data about the outside world, and intelligent systems to decipher some meaningful information from this data. At a more fundamental level, however, it seems that these two frontiers are not discrete in any way; rather, they provide progress towards the one true goal that is the gathering of intelligence about the world. Unsurprisingly, there are many types of sensors in computing and robotics. Here, we'll discuss two such sensors: **LiDAR** and the **accelerometer**. Each of these devices are built on the simplistic, beautiful principles of both Newtonian and quantum physics, and the ingenuity of their design can be credited with many of the functions of technology that we take for granted today.

LiDAR, short for *Light Detection And Ranging*, is an active sensor system which involves the emission of photons whose wavelengths reside in the ranges of ultraviolet, visible, or near infrared light, and the subsequent measurement of the reflection of these photons. In other words, LiDAR shoots laser beams out to the environment, and then reads the reflected light which is "bounced back" to the sensor. The sensor uses the time delay between emission and perception, as well as differences in wavelength, to determine the distance between itself and objects in its environment. Then, this information is used to create a sort of "map" of the world around the device which houses the sensor, an illustration of which can be seen below in *figure 1* [1].

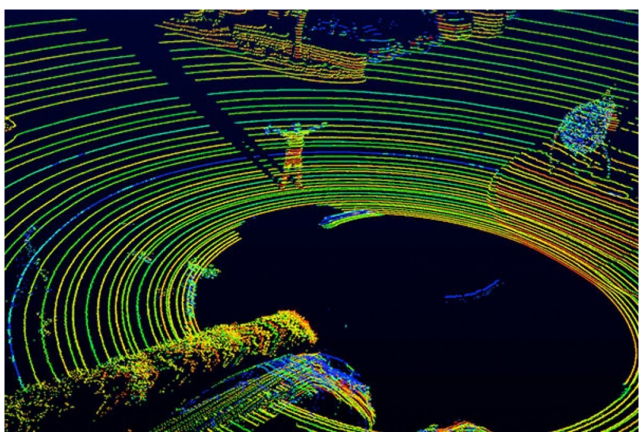

figure 1: Illustration of LiDAR map

As can be inferred from its capabilities, LiDAR is an exteroceptive sensor, providing information to the device about the external environment surrounding said device. LiDAR has gained quite a bit of popularity in recent years due to the development and advancement in such fields and industries as robotics, artificial intelligence, and transportation; however, the technology itself is certainly not new [2]. The first system that functioned in the same way as the modern LiDAR system was developed in 1961 by the Hughes Aircraft Company [3], shortly after the invention of the laser. Soon after its inception, LiDAR saw use in the observation of pollution and cloud coverage [4]. In the approximately 60 years since those days, LiDAR has been extensively used for terrain-mapping, wherein LiDAR sensors are fitted to the bottoms of airplanes and pointed at the ground. In systems such as these, LiDAR must be used in conjunction with GPS and accelerometers (discussed later) to provide detailed information about terrain at a given set of coordinates on the Earth's surface [5]. Furthermore, the development of LiDAR is not yet complete: In 2019, a collaboration of researchers showed that the exploitation of quantum physics can significantly increase signal-to-noise ratio (SNR) in LiDAR systems using the ingenious exploitation of quantum physical properties in order to threshold low photon numbers in LiDAR signals, thereby filtering out noise [12]. (In fact, the lasers which are fundamental to the basic design of LiDAR are themselves inherently quantum; their existence can not be explained through mere classical mechanics [13]). Just earlier that same year in March of 2019, SpaceX, the world's first successful private space company, created a custom version of LiDAR to assist in the docking of their spaceship, the Dragon, to the International Space Station (ISS) [6]. In fact, this incredible feat, achieved with the help of LiDAR, was the single event that granted the company with the admittedly subjective aforementioned title of "first successful private space company", backed by their newfound objective title as the first ever privately-held space company to send a rocket to the ISS!

However, for all of the benefits afforded to a system containing LiDAR, the technology is quickly becoming obsolete in the face of artificially intelligent computer vision systems. To see why this is the case, it is important to sift through all of the unnecessary details and ask ourselves: what is LiDAR doing? The answer is quite simple: LiDAR is using visible light to perform depth perception. If this sounds familiar, it should. **That is exactly what human vision does**. We gather a sense of depth perception from the coagulation of a few different sources. Firstly, because we have two eyes, our visual cortex triangulates the positions of objects in our environment by calculating the difference between visual signals received by either eye. Secondly, we use the motion of our own body relative to the motion of our environment to further augment our purely memory-less depth perception. Finally, and perhaps most crucially to the modern argument against LiDAR, we utilize **memory** to "fill in the blanks" when we invariably are caught in situations in which we can't view the entirety of objects. Since the moment we're born, we amass a huge agglomeration of knowledge about objects, and in our mind's fervent, eternal quest to simplify the world, we categorize these objects. Then, any time we use our vision to judge and analyze the details of our environment, including the distance between ourselves and objects in that environment, we learn to do one of two things: either we place the objects that we see into one of the many categories that we have stored in our memory, or we create a new category with which to store these objects.

As a thought experiment, imagine that you're standing in the middle of a large swath of land in the center of a tundra. There are no objects in your line of sight before the horizon in any direction, save for one: out in the distance, you see an object in the general shape of a rectangular prism. Without any sense of memory, you might have no idea whatsoever how far that object is from your person. However, you focus on the object, and you see some defining characteristics: the frontal third of the prism is much shorter in height than the rear two-thirds. Your brain begins to theorize about the category of the object: is it a car? You squint slightly, and with the assumption that the object may be a car, you see the outline of what must certainly be tires, followed by a cutout for headlights and taillights, and so on. At a point, you become certain that the object is a car, and given your stored memory of the size of cars, you ascertain that the object is no closer to you than a mile.

This thought experiment is just a small example of the crucial effect that context and memory plays in the effectiveness of depth perception. Computer vision algorithms are experiencing astounding levels of growth, and this notion of categorization of objects using memory, and subsequently using this categorization to augment depth perception is possible today with modern object detection and computer vision powered by deep learning [11]. Essentially, the issue with LiDAR in the face of computer vision is that it simply doesn't do anything that computer vision can't. Furthermore, LiDAR is expensive and complicated when compared to passive optical cameras, and provides no functionality other than depth perception [9]. What's more, LiDAR employs the promising idea of "echolocation", whereby an active sensor emits electromagnetic radiation to the environment and measures the return signals, but it doesn't utilize the wavelengths of light that can penetrate objects, as does radar, and is therefore limited by line of sight, unlike radar. For these reasons, LiDAR is a fantastic technology, but is simply less generalizable and capable than sufficiently mature computer vision systems. In other words, LiDAR works, but it's a shortcut, and a limited one at that.

Accelerometers, in contrast, are a technology which may be more immediately familiar to consumers, and which are a far more fundamental type of sensor. Accelerometers are used to measure acceleration, and can leverage the constant acceleration of gravity to calculate the orientation of a device. As an example, when Apple released the first iPhone in 2007, the device included an accelerometer which could be used to detect the orientation of the phone for use by applications such as games, internet browsers, music players, and more. While the measurement of acceleration may seem to be a relatively simple task, it stands that acceleration is a mechanical phenomenon which must somehow be measured by an electronic device. This is an interesting issue, one which has been solved by the ingenious design of Micro Electro-Mechanical Systems (MEMS). MEMS appear similar in form to integrated circuits, but are in fact mechanical circuits designed to be as small as physically possible. MEMS accelerometers are implemented with the use MEMS capacitors, where a small piece of silicon acting as a weight is attached to the end of what is referred to as a combed-finger arrangement, wherein the two terminals of a capacitor have silicon "fingers" which are arranged in parallel [10]. A picture of such a device can be seen below in *figure 2*.

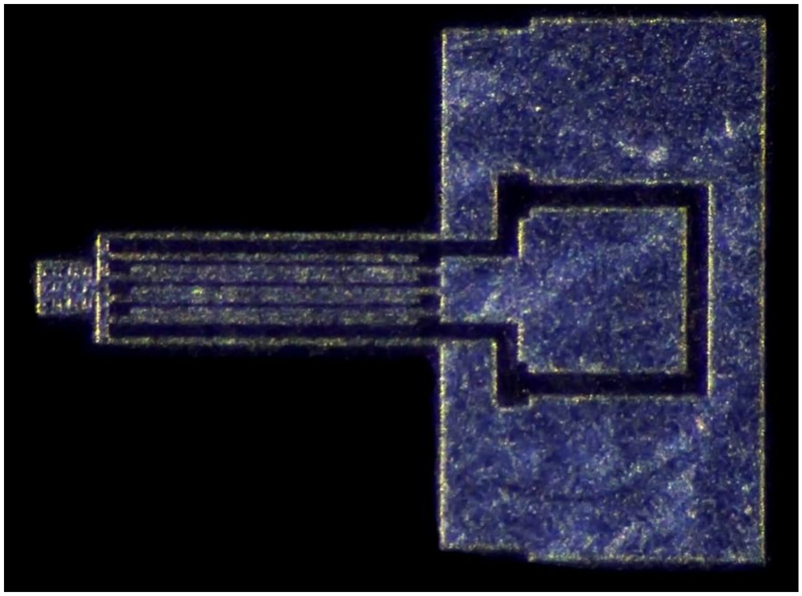

figure 2: MEMS accelerometer

The motion of this small silicon weight due to gravity, change of direction, vibration, or any other source of acceleration affects the position of the fingers which are attached to one of the terminals of the capacitor, thereby changing the distance between the fingers of the two terminals, and creating a change in capacitance. Then, circuitry can be created which can sense this change in capacitance and convert the resultant signal into synch useful data as voltage levels or serial data. Finally, this data can be used to deduce acceleration. Likewise, this acceleration can be used to deduce a number of physical effects on the device such as linear acceleration, orientation, and vibration. Further up the abstraction pipeline, one could use 3 of these accelerometers, one for each dimension, and could then deduce the exact orientation of a device at any given time relative to the Earth's surface. It's not a difficult task to imagine the importance of such a sensor: In an airplane, accelerometers can be used to determine the three principal axes of aircraft: pitch, yaw, and roll. This data is absolutely necessary to the function of autopilot systems, manned and unmanned drones, and more. Furthermore, a robot can use accelerometers to determine the relative stability of a surface in addition to information about its spatial orientation. As can be seen, the list of use cases for accelerometers is nearly boundless.

While much of the modern attention on robotics and technology is paid to the intelligent software systems which create detailed models of the internal and external environments of a device, sensors are at the core of all of these advances. LiDAR is a fascinating and useful technology which leverages the power of electromagnetic radiation to create detailed maps of objects in an environment. These capabilities have allowed LiDAR to see use in terrestrial mapping, weather monitoring, autonomous vehicle development, and more. However, the days of LiDAR are quickly coming to an end, as the technology is simply limited by nature. With the advances in deep learning paving the way for mature, robust computer vision, Accelerometers are a simple device founded upon the principles of simple Newtonian physics and electrical engineering, yet enable the creation of autonomous planes and location-aware handheld devices. Without accelerometers, flipping the orientation of a smartphone or tablet would require an unintuitive, annoying press of a button, an action which would further increase the distinction between true physical reality and virtual reality that we strive so ardently to minimize. Furthermore, the creation of MEMS has been crucial in the integration of devices such as accelerometers in the small PCBs of everything from smartphones and computers to airplanes and boats. Recently, in 2011, researchers from Harvard developed a new kind of MEMS-based accelerometer created not using silicon and silicon dioxide, but rather on paper[7]. This research is a promising look into cheap, simple alternatives to traditional silicon-based computing materials, and has inspired new research efforts as soon as 2018, when a paper by Y. Wang, P.Song, X. Li, C. Ru, G. Ferra[8] further implored the use of paper as a medium for MEMS chips. The development of sensor technology is a crucial endeavour which will require the collaborative effort of engineers from all disciplines, and is truly at the forefront of the development of robotics and technology as a collective.

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