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HyperSpectral Technology for Autonomous Vehicles

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EXECUTIVE SUMMARY

The goal of autonomous vehicles is simple: change the world by providing vehicles that safely navigate humans to where they need to go without the human's input. In order to provide what might be one of the clearest pictures of science-fiction coming to life since the cellular phone, automotive manufacturers and service providers need to prove that this technology will be better-than-human in terms of safety and accident avoidance. What is science-fiction today is already becoming increasing consumer demand.

This landscape examines the role HyperSpectral (HS) imaging devices will play in this effort, in what will be a collision of the imaging industry with the automotive market to enable autonomous vehicles to enter the marketplace and our lives.

HyperSpectral imaging provides a technological solution for gaps that current autonomous vehicle players have failed to achieve, and offers better-than-human safety than one most visible-light spectrum sensors can achieve. The breadth of data available when properly harnessed will be more valuable than the data currently collected from visible light sensors alone - offering a market opportunity for new players to get involved and catch-up with industry leaders in autonomous vehicles, chiefly Tesla and Waymo.

Already in use in several industries and scientific research efforts including geography, climate monitoring, agriculture, and mining, to name a few, HyperSpectral imaging sits on the outside of the autonomous vehicle market today while automotive manufacturers continue to experiment with data imaging only across a few spectrums of light. There is at present a robust ecosystem of players from auto manufacturers, vehicle services, software companies, processor/chip manufacturers, and sensor manufacturers all having a unique opportunity to capitalize on HyperSpectral imaging through research and development, vertical or horizontal integration, and automotive manufacturing.

These opportunities for investment in either hardware or software solutions to support HyperSpectral in vehicles will reward any industry player who can successfully miniaturize and implement these existing technological offerings into a vehicle cost-effectively, overcoming cost as the largest challenge that Hyperspectral currently faces as a primary inhibitor for adoption in addition to government regulations and privacy concerns.

SAFETY OF AUTONOMOUS VEHICLES

Autonomous vehicle accidents in the news

Today's autonomous cars belong to the level 0 – 3 category of autonomy. These require some level of user monitoring / intervention during driving. As we look ahead to transition to level 4 -5 autonomy, there are few challenges that we need to address – SAFETY – being the first and foremost. Let's take a look at some of the infamous accidents related to semi-autonomous vehicles in the recent past.

Figure 1: Autonomous vehicle accidents in the news

In the first incident above, [1] *Uber car involving a bicyclist, according to NTSB report - system consisted of forward- and side-facing cameras,camera system mounted on windshield and rear window ,radars, LIDAR (Light Detection and Ranging) , navigation sensors, and a computing and data storage unit integrated into the vehicle. The bicycle had front and rear reflectors and a forward headlamp, but all were facing in directions perpendicular to the path of the oncoming vehicle. As the vehicle and pedestrian paths converged, the self-driving system software classified the pedestrian as an unknown object, as a vehicle, and then as a bicycle with varying expectations of future travel path. According to Uber, emergency braking maneuvers are not enabled while the vehicle is under computer control, to reduce the potential for erratic vehicle behavior. The vehicle operator is relied on to intervene and take action. The system is not designed to alert the operator.*

The second incident above involved [2] *collision of a Tesla Model 3 car with a semi-tractor trailer on a highway. Tesla informed the NTSB that the installed forward collision warning and automatic emergency braking systems on the Model 3 Tesla in the crash were not designed to activate for crossing traffic or to prevent crashes at high speeds and therefore, according to Tesla, the "Autopilot" vision system did not consistently detect and track the truck as an object or threat as it crossed the path of the car.*

In the third incident above, [3] *Tesla Model X P100D electric-powered sport utility vehicle (SUV), was traveling south on Highway. The car continued traveling through the gore and struck a previously damaged and nonoperational crash attenuator at a speed of about 71 mph.* Among other reasons including driver distraction, NTSB also noted the limitation of the collision avoidance systems. [3] *The Tesla's collision avoidance systems were not designed to, and did not, detect the crash attenuator. Because this object was not detected, (a) Autopilot accelerated the SUV to a higher speed, which the driver had previously set by using adaptive cruise control, (b) the forward collision warning did not provide an alert, and (c) the automatic emergency braking did not activate. For partial driving automation systems to be safely deployed in a high-speed operating environment, collision avoidance systems must be able to effectively detect potential hazards and warn of potential hazards to drivers.*

Whereas two of these incidents occurred in darkness, the third incident was in daylight. While technology is evolving at a fast pace, it is imperative that we overcome the limitations of existing technology to make autonomous cars safer. Hyperspectral camera based autonomous cars can enable detection and classification of objects of any type of material and enable the collision avoidance module to prevent such incidents.

Why HyperSpectral Cameras?

Since hyperspectral cameras capture more information than visible spectrum cameras, they are less sensitive when operating in the dark, in direct headlight or sunlight glare, in quick changing light environments, and through fog.

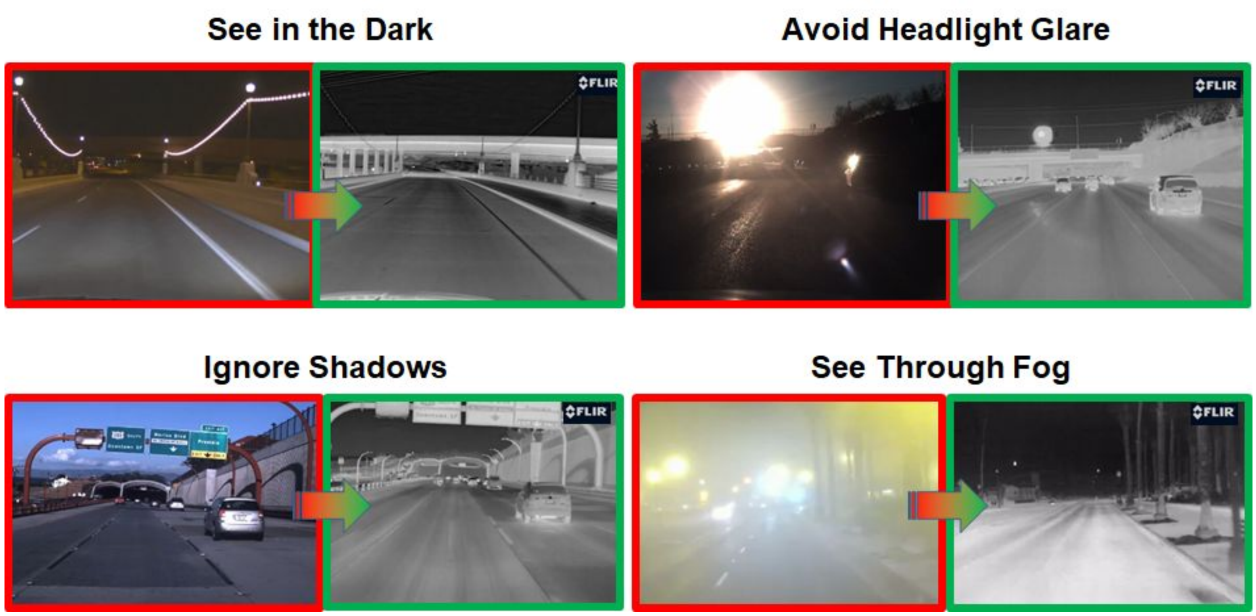


Figure 2: Advantages of HyperSpectral

Hyperspectral cameras use spectral filters in multiple wavelengths to provide an enhanced situational awareness that can cut through visible light interference and limitations.[4]

How does HyperSpectral technology work?

Hyperspectral cameras record over 100 different wavelengths, covering a much broader color spectrum from UV to infrared light. The ability to visualize the infrared spectrum enables the precise identification of specific material signatures or "material fingerprinting". As a result, materials can be clearly identified and classified based on their chemical composition.[5]

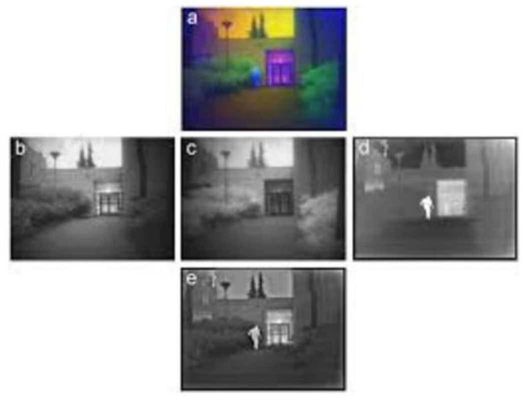
How does a hyperspectral camera work? 1. Camera captures a HyperSpectral frame data (a) 2.Filtering of the picture provides focus on various parts of the frame, highlighting 3.Building (b) 4. Door (c) 5.Person (d) 6.A combination of person and door (e)	

Figure 3: HyperSpectral Camera - Operation and Filtering

HyperSpectral Technology could disrupt autonomous vehicle market

As of 2020, the lion's share of (semi) autonomous car market belongs to none other than Tesla. Although there are multiple players in the market (Waymo, Uber, etc) they have much smaller market share.[6] *Tesla's use of data, AI (Artificial Intelligence) and ML (Machine Learning) to build a neural network - a system of sensors, data, communications, CPUs, peripheral hardware, and software that collectively processes information and adapts and learns like a human — is where the company really shines. It will take millions of hours of coding, defining and refining algorithms, sophisticated 3D modeling and simulations, test tracks, even beta testing in real life situations.At least, that would be the case if you used the traditional approach. But that is not what Tesla is doing. It is doing something quite novel. With 600,000 cars on the road, Tesla treats each vehicle, each sensor, each "event" (i.e. human interaction with the steering wheel, brake pedals, etc.) as data points. It is then taking that data, analyzing it and utilizing it to improve its algorithms, create new algorithms and send those improvements over the air to the vehicles. As of November 2018, Tesla has amassed 1 billion miles of Autopilot data. For comparison, Waymo has collected about 15 million miles.*

According to a report based on Tesla tear down - What stands out most is Tesla's integrated central control unit, or "full self-driving computer." Also known as Hardware 3, this little piece of tech is the company's biggest weapon in the burgeoning EV market.

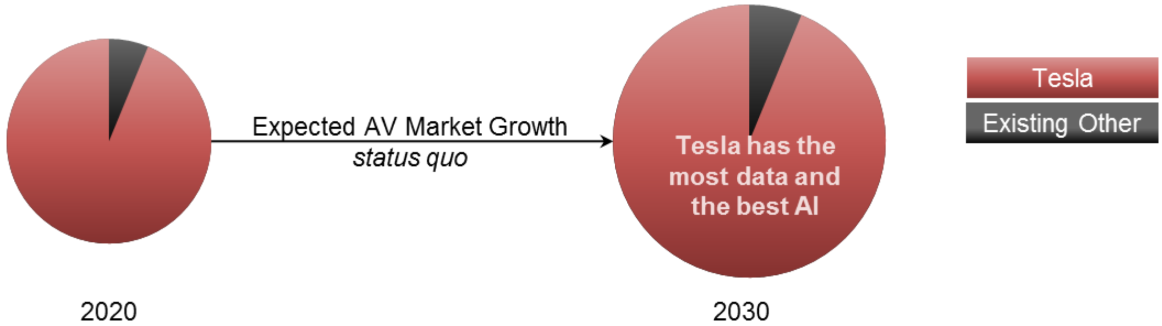


Figure 4: Advantage Tesla with status quo due to leadership in technology & data collection

If the existing technology enabling data collection and AI/ML tuning continues as it is, Tesla will continue to lead the market share in the next 6 – 10 years. However, with HyperSpectral camera-based object classification (HSCBOC) this landscape could change significantly. The fact that data captured by a HyperSpectral camera is highly rich and provides a fingerprint for every entity in the image, the data could be dynamically processed at real-time and used to classify/identify them. Outsight[8] has demonstrated this method of image processing and classification using low power processors without requiring complex AI algorithms. We believe this is a key enabler for multiple other players in the Autonomous Vehicle market. This could be the equivalent of google maps of self-driving cars to generate a static map of a roadway which can significantly mitigate accidents related to fixed objects on roadways. Further, this could be overlapped with dynamic objects and provide a means to safer self -driving cars. This could be a major disruptor in the Autonomous Vehicle (AV) industry. The arrival of more players could in turn facilitate AV related Government regulations to advance, changing the ecosystem to the benefit of AV market growth. New players in the market would have a great impact on the distribution of market share.

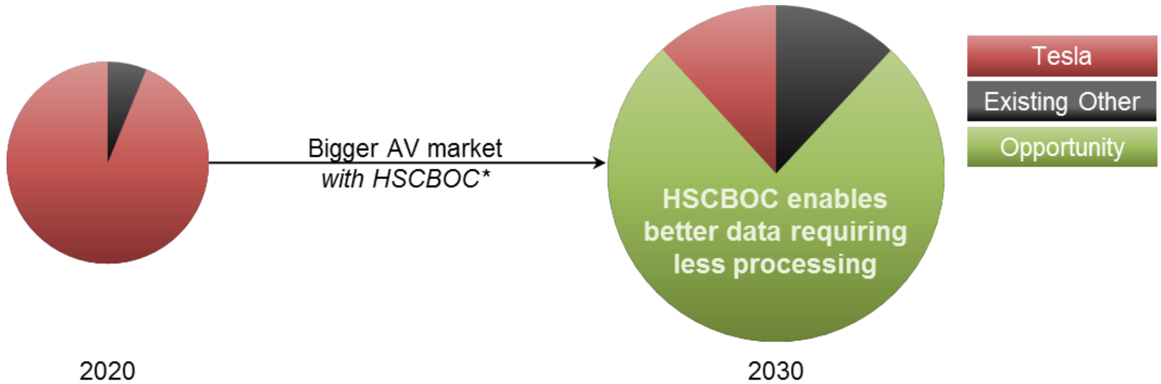


Figure 5: HyperSpectral Camera Based Object Classification (HSCBOC) could level playing field

Overview of Automotive Market Ecosystem

The automotive ecosystem is expanding globally and the future may grow even more. The urbanization, increasing per capita income and the rising standard of living is going to drive the demand for automobiles all over the world. The evolution in technology, change in consumer preference and tightening regulations, could add up to a fundamental shift in the automotive market. The traditional five-to-eight year life cycle of a vehicle, which has always been common in this automotive industry, could soon be a thing of the past. Instead, automobiles will be updated annually in order to integrate the latest hardware and software developments. The automotive ecosystem with autonomous vehicles, and shared autonomous vehicles in particular, will have higher usage and frequent updates utilizing the latest technology. This coupled with the increase in disruptive ride-sharing applications should result in another driver towards rising automobile sales.

The disruptive trends in the automotive market such as electric, autonomous, connected and shared automobiles will lead to a clear increase in the rate of innovation within the automotive industry. As the high-tech and automotive market merge, customer preferences are moving away from its traditional vehicles. The shift in customer preferences and the size of the automotive sector has attracted new players with a mix of large high-tech companies and start-ups. These new entrants and the disruptive trends such as electrification, autonomous driving, diverse mobility, and connectivity will transform vertically integrated automotive value chains into a complex, horizontally structured ecosystem.[10]

With this change in the automotive ecosystem, the operating models of traditional OEMs differ from the new tech entrants in the automotive industry. As per McKinsey study, *"the convergence of the automotive and high-tech sectors will rewrite the rules of competition and lessen the chances of survival for traditional players that fail to act. The competitive space remains fluid at this point, but that could change quickly as incumbents move to position themselves advantageously and tech companies solidify their investment strategies"*.[11] With the transformational change, OEMs and tech entrants should align their skills and processes to address new challenges such as cybersecurity, data privacy, and continuous product updates.

Overall, the study shows that global car sales will continue to grow and the new business models could expand automotive revenue pools by about 30 percent, adding up to $1.5 trillion in additional revenue potential in 2030, compared with about $5.2 trillion from traditional car sales [9] and aftermarket products/services, up by over 50 percent from about $4 trillion in 2019.

Opportunity for HyperSpectral cameras in the automotive market

As seen in the previous section, the automotive market is thriving & expanding. However, what about the automotive camera market?

For 2019, here is a bottom-up approach to estimating the Total Addressable Market (TAM) of the automotive camera market –

[**75M** *Cars*][29] × [**5%** *Leve2+ Cars*] × [**7** *Cameras per Level2+ Cars*] × [**$300** *Cost Per Camera*] = **$7.9B**

Assumptions in the above bottom-up TAM estimate might be conservative. E.g., some estimates have attach-rate of Level2+ cars at 10%[12] for the US in Q2'19 and cost of cameras per car at $6,000[13] compared to the assumptions of 5% attach rate for Level2+ cars and $2,100 (7[14] × $300[15]) for the cost of cameras per car respectively in the bottom-up calculation shown above. For additional comparison, looking at several market research reports also point to a TAM in high single-digit billions of dollars for 2019. For example, Markets & Markets estimated $8.2B in its November 2019 report. When it comes to predicting the growth of this market, CAGR estimates in these research reports range from 10% to 20% for the next 5 years. That is pointing to a $15.1B to 23.3B market by 2025.

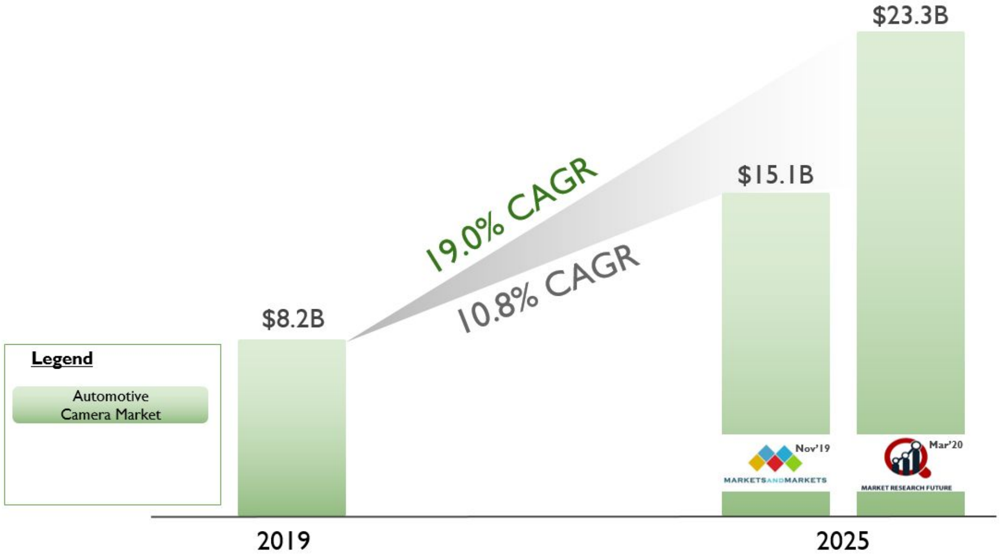


Figure 6: Automotive Camera Market

Given the limitations of existing visible spectrum sensor technologies, here's a prediction about adoption of HyperSpectral cameras in the automotive camera market – attach-rates expected to reach over 90% by 2025, if not being able to replace 100% of visible spectrum cameras. This results in a TAM of $13.6B to $21B in 2025. That is a market with the potential to go from pretty much zero to $21B in 5 years.

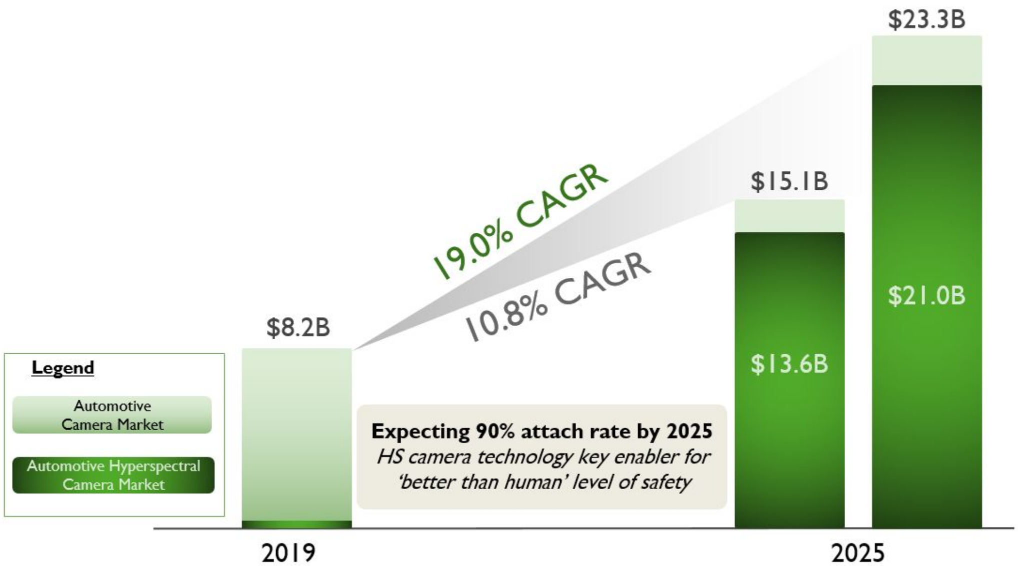


Figure 7: Adoption of HyperSpectral cameras in the automotive market

Remember, this is just the automotive camera market. HyperSpectral cameras are already used in other industries like agriculture & mining. The HyperSpectral camera market is poised to explode in the next 5 years.

ADOPTION OF HYPERSPECTRAL TECHNOLOGY

Cost vs. Autonomy

As discussed earlier, visible spectrum cameras have safety limitations recognizing hazards at night, in poor weather conditions, in bright lights or in shadows. Hyperspectral cameras can use wavelengths from IR to visible to UV to get additional spectral information to alleviate these limitations. None-the-less, the hazard needs to be in the field of view of the camera, and like all cameras, hyperspectral cameras have a finite viewing angle (figure 8 below). Munster predicts level 4/5 vehicle autonomy will require 10 – 12 cameras to provide near 360-degree perception to perform lane departure detection, traffic signal recognition, and parking assistance.[17]

Due to their low-price point and lower computational requirements, visible spectrum mono-cameras are currently the primary computer vision solution for advanced driver assistance systems (ADAS). Having multiple advanced imaging units such as MultiSpectral or HyperSpectral cameras will exacerbate the cost challenge.

Mono-cameras can identify lanes, pedestrians, traffic signs, and other vehicles in the path of the car, all with good accuracy; however, they cannot accurately discriminate size from distance. This could lead to delayed or premature response to hazards. Just as humans use two eyes for depth perception, autonomous vehicles can employ dual-lense, stereo cameras. The dual lenses, along with the computational challenges associated with overlaying dual images will further increase the cost challenge. Another option is using LiDAR for depth perception to create 3D models of the car's surroundings; however, LiDAR has limitations in adverse weather conditions. In the pursuit of level 5 automation, a combination of several imaging technologies will likely be used to meet the cost targets needed to serve the general automobile market. For example, Tesla today uses a combination of 8 visible cameras, 12 ultrasonic sensors and a forward-facing RADAR (Figure 10).

In order to achieve level 5 Automation, the number and capability of the imaging components will need to increase. Visible cameras and ultrasonic sensors are commodity products and a system can be put together for less than $5,000; however, the autonomy achieved with this type of system will likely never progress beyond level 3. LiDAR systems are in the market and vary in cost depending upon a variety of factors, as illustrated in Figure 11. LiDAR will need to be complemented with another imaging technology such as vision; but will likely not extend beyond level 4 automation without data outside of the visible spectrum.

We believe visible cameras will not provide the level of safety required to achieve full autonomy, so either MultiSpectral or HyperSpectral cameras will be required. Multispectral imaging might evaluate an image in three or four colors (red, green, blue and near-infrared (NIR), for example) while hyperspectral imaging breaks the image down into tens or hundreds of colors. Examples of MultiSpectral camera costs are provided in Figure 12. Up until recently, HyperSpectral cameras have mainly played in the military and scientific arena[20] due to their complexity and costs in the millions of dollars. What once required large, delicate, and expensive laboratory spectrometers is now being done in real time aboard satellites, unmanned aerial vehicles, and portable handheld units. New technologies such as inexpensive, high quality diffraction gratings and thin film filters deposited on the active CMOS imaging sensors combined with advanced multiple dimension data processing have brought commercial products under $100K.[21]

Figure 13 below pictorially summarizes the trade-off between autonomy and cost. For HyperSpectral imaging to find commercial success in the autonomous vehicle market, the cost needs come down another 1-2 orders of magnitude.

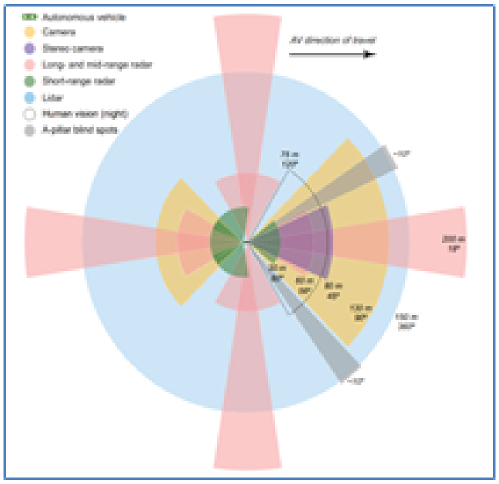


Figure 8: Example illustration (drawn to scale) of the various sensors, with reasonable estimates of coverage area (field of view) and typical operating ranges, for both a human-driven vehicle as well as a hypothetical AV [16]

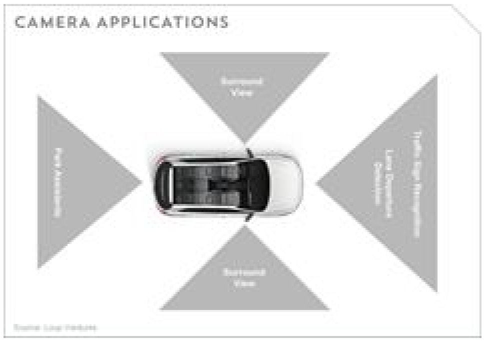


Figure 9: 360 degree viewing requirements

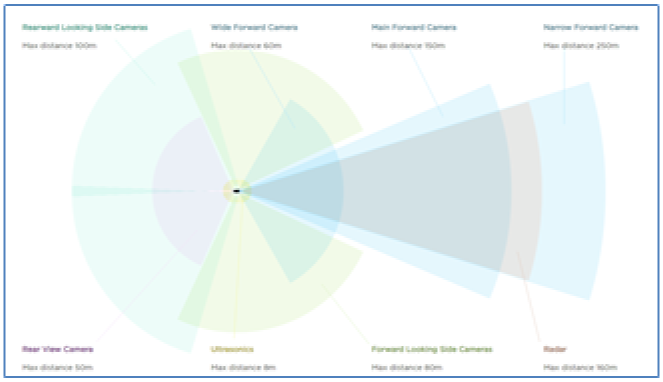


Figure 10: Tesla Advanced Sensor Coverage[18]

ADAS vehicles / Robotic vehicles	Valeo	Velodyne LiDAR	Velodyne LiDAR	Velodyne LiDAR		OUSTER
Model	Scala 1	HDL-64	HDL-32	VLP-16	RS-LiDAR-32	OS-1
Channels	4	64	32	16	32	64
Range (m)	100 - 200	100 - 120	80 - 100	100	200	100
Data rate (pts/sec)	NA	1,300,000	700,000	300,000	640,000	1,310,720
Horizontal resolution	0.25°	5Hz: 0.08° 10Hz: 0.17° 20Hz: 0.36°	5Hz: 0.08° 10Hz: 0.17° 20Hz: 0.35°	5Hz: 0.1° 10Hz: 0.2° 20Hz: 0.4°	5 Hz: 0.09° 20 Hz: 0.36°	0.18°
Power (W)	7	60	12	8	13.5	NA
Operating temperature	NA	-10° to 50° C	-10° to 60° C	-10° to 60° C	-10° to 60° C	NA
Cost ($)	$600	$75,000	$30,000	$8,000	$16,800	$12,000

Figure 11: Sample LiDAR system costs[19]

Product	Cost
FLIR T1020 HD	$40,000
Micasense Altum	$10,000
Parrot Sequoia+	$3,500

Figure 12: Sample MultiSpectral camera costs

Figure 13: Trade-off between cost and automation levels[22]

Low cost HyperSpectral cameras are in the horizon

At an average cost of $20,000-$100,000 USD per unit, it is easy to see why HyperSpectral imaging has seen slow adoption in automotive applications. Even at the bottom-end of this spectrum implementation of these devices effectively doubles the average cost of a compact car.[26] In the face of these costs, recent research and development efforts into HyperSpectral imaging technology may be indicating these devices have reached a high watermark in cost. As efforts to miniaturize HS technology and reduce costs for potential implementation into mobile devices have begun, a handful of firms may have possibly opened the door to a significant cost reduction for HyperSpectral imaging across the board.

In 2015, partnering with Microsoft Research, University of Washington's Paul G. Allen School of Computer Science and Engineering worked to develop HyperCam, a low-cost HyperSpectral imaging device coming in at approximately $800.00. The team was eventually unsuccessful at miniaturizing the tech to a reasonable size for a mobile device or smartphone but determined potential use-cases for their Hypercam (which notably excludes automotive) including food / agriculture, healthcare, and biometric security applications. Even though automotive manufacturing was not on their list of potential applications the learnings from HyperCam indicate an incredible opportunity for cost reduction in HyperSpectral imaging [23].

VTT research also embarked on a similar effort to miniaturize for mobile devices and in designing their Fabry-Pérot Interferometer (FPI) technology, they have managed to do so successfully at a bill of materials cost of $150. They also believe that their technology is mass-producible and at scale has the potential to reach approximately $20.00 USD for the optics technology.

Neither VTT's FPI / MEMS technology or HyperCam may be immediately capable of integration into a vehicle but solving the optics and processing challenge greatly improves the available opportunities for autonomous vehicles to leverage this technology. The opportunities for the technology is clear and VTT Research may say it best: "Hyperspectral imaging is to photography, what photography was to painting, a revolution."[25]

The learnings from HyperCam in particular also outline some other challenges HS has overall: privacy. The mention for biometric security among the potential applications for HyperCam indicated that HyperCam could differentiate the hands of different people with 99 percent accuracy.[24] While this could be an incredible breakthrough in security tech for first or second-factor authentication, it raises all of the same security concerns as fingerprinting as the HyperCam was able to do this simply by seeing the vein patterns underneath the skin as well as unique patterns of a person's skin texture.[24] The privacy implications here as the technology advances will definitely need to be addressed should HyperSpectral see the light of day in an automotive form-factor that travels unlike a static fingerprint reader on a door - and can measure these signals without near-or-direct contact again, like a fingerprint reader would usually require.

These challenges aside, even without automotive as an immediately available use case, device or sensor manufacturers for HyperSpectral have a clear market opportunity- as would their investors.

DISRUPTIONS AND LIKELIHOOD

By 2025, there are several opportunities for HS cameras to disrupt the current autonomous vehicle landscape. Factors such as lower cost, spectral image data capture, opportunities for new players and adoption to infrastructure are enablers to HS camera adoption.

Standard monochrome visible cameras have 75% likelihood of being replaced. HS cameras have greater image collection capabilities that monochrome cameras cannot achieve. The downside is HS camera costs could inhibit the adoption timeline.

Lidar systems are expensive and have a 50% likelihood to be replaced by HS cameras. Multiple HS cameras can be used to estimate distances and offer more details in image data in multiple spectrums. However, an inhibitor to this adoption is costs are declining for lidar sensors due to advancements in lidar manufacturing processes.

A disruption of a creating a level playing field has a 75% likelihood of becoming an opportunity for HS cameras. The enabler for the disruption centers around the vast amount of spectral data HS cameras can obtain. By collecting large spectral data sets, there is less processing and requires less complex algorithms to classify an object. The inhibitor's initial high costs could be a barrier for entry.

Infrastructure has a 75% likelihood of adoption with hyperspectral cameras. The enablers that contribute to the adoption are increased safety with connected vehicles and additional information available for surveillance and insurance accident claims. Based on the amount of data collected and how it's used, the inhibitors may have privacy concerns and government regulations associated with implementation of hyperspectral cameras.

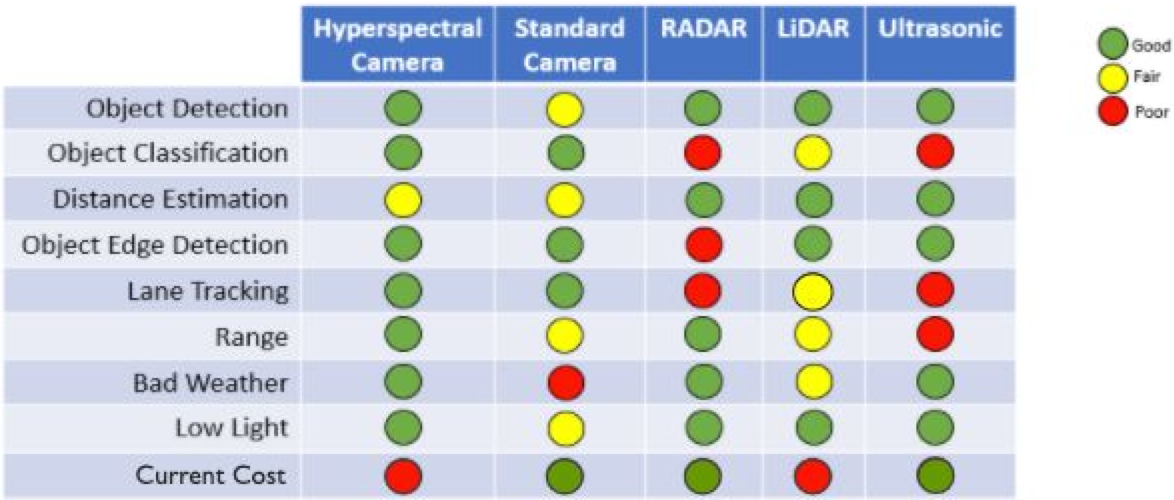


Figure 14: Hyperspectral camera adapted in part to http://umich.edu/~umtriswt/PDF/SWT-2017-12.pdf

Government and Privacy Concerns

The high level of detailed data hyperspectral cameras can capture is large compared to the standard AV (autonomous vehicle) sensor suite. Misuse or data breaches have concerns both in the public domain and government agencies.

In 2016, a consortium of vehicle manufacturers established the Automotive Information Sharing and Analysis Center (Auto-ISAC). DOT's autonomous vehicle policies designate Auto-ISAC as a central clearinghouse for manufacturers to share reports of cybersecurity incidents, threats, and violations with others in the vehicle industry.[27] Consumers, legitimate companies developing AV (autonomous vehicles) and government agencies would have access to the collected data but there is no clear method of managing how the data will be used. Further development and agreements within Auto-ISAC would be required to protect both the end user and public from misuse of the data. At present, no laws preclude manufacturers and software providers from reselling data about individual vehicles and drivers to third parties. [28]

KEY TAKEAWAYS

The goal of autonomous vehicles is simple: change the world by providing vehicles that safely navigate humans to where they need to go without the human's input. We believe HS Imaging will deliver the better-than-human safety and accident avoidance autonomous vehicles consumers demand. Already in use in several non-automotive industries, HyperSpectral imaging technology has shown clear benefits to detect hazards that the imaging technology currently employed in automotive applications can fail to see.

Recent miniaturization and manufacturing advances show promise to bring the cost of the technology down to the level needed for mass market automotive applications. The technology is ready and the price is dropping. HS Imaging provides many business and investment opportunities in both hardware and software solutions. By exploiting HS Imaging's better data and less processing, we believe a new player could become the next leader in autonomous vehicles and bring full autonomy to the masses.

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