LiDAR measurements in Maritime transport safety and navigation of the deep seafloor

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***Abstract*— This paper provides an insight into how LiDAR can be applied for the benefit of shipping, sea and ocean traffic, as well as for navigation and detection of the deep seafloor. The current measuring and control methods of this sensor are presented along with the used equipment. The principles of sensor operation are described. The aim of this paper is to emphasize the future applications of LiDAR in ocean transport and its safety, as well as the detection and visualization of the underwater world and its hidden objects.**

Index Terms—LiDAR; maritime; safety; seafloor; sensor; airborne; shipping; bathymetry; laser.

I. Introduction

Nowadays, LiDAR (*Light Detection and Ranging*) is widely used in order to examine various properties of the atmosphere, in autonomous driving and many other aspects such as mapping and topography. LiDAR's possibilities in autonomous driving are highly evolving these days but, if we think about the other types of traffic such as oceanic transport, or transportation and navigation in general, we can see that it is not developed and utilized enough to fulfill the needs for a safer transport. This topic is possibly disregarded because of the limitations in the underwater use, which seem to cause more issues regarding its development, in comparison to LiDAR's use in the atmosphere and earth's surface. In this paper, the discussion on how LiDAR can be used to benefit shipping, navigation, autonomous navigation, present weather measurements and detection, is made and some proposals are given. The scope of this work is to present the multiple usages that LiDAR can offer in shipping together with a total proposed solution for the deep seafloor and underwater world detection. New and unfamiliar usages of LiDAR that could change the future in many ways are given some thought. I would like to emphasize the possibility of LiDAR's role in coastline protection, biological analysis of deep seafloor species, animals, algae's and other water plants and sea sponges. Also, one of the interesting applications are detection of water salinity levels and the analysis of chemical properties of underwater minerals. Later, we will mention a few more applications of LiDAR with their advantages, that could bring humanity more knowledge regarding the underwater world.

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II. Working principle of LiDAR sensor

LiDAR represents a digital optical measuring device for the detection and range of light. It is a remote sensing method that uses light in the form of a pulsed laser beam to measure the range, more precisely the variable distance to Earth. This sensor emits laser output pulses that have variable frequencies and intensity, while pulsed rays pass through the project area. Outgoing impulses are reflected from the surface objects and from the ground, and later, they are detected and captured by the sensor itself. The time delay between transmission and detection of each feedback pulse provides the distance from the sensor to the surface object, producing its 3D model [8].

In general, when we speak about the working principle of LiDAR, it is similar to EDMI devices [17], where a pulse, continuous wave or laser is fired from a transmitter, and later the reflected energy is captured.

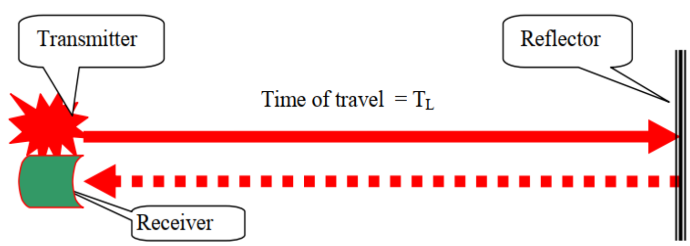

Fig. 1. Range measurement using laser principle [8]

The measuring distance from the transmitter and the reflector is determined by calculating the time of travel (T_L / ToT). In some specific cases, the role of the reflector can be some natural object or an artificial reflector such as a prism. A laser pulse is emitted from an aircraft, to measure the terrain elevation from the time between emission and reception of reflected pulses. Measuring distance provides the coordinates (x, y, z) of the reflector.

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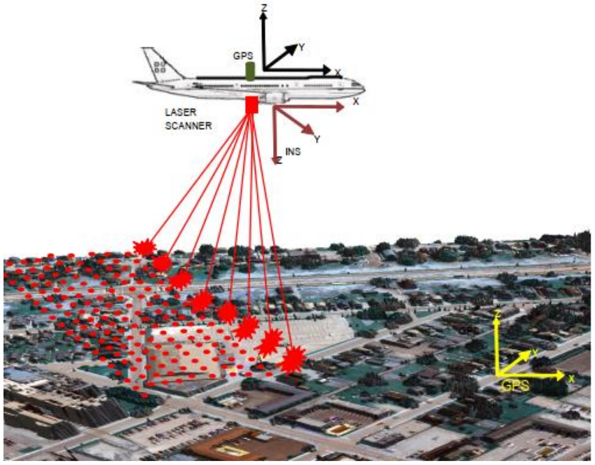

Fig. 2. LiDAR topographic system [8]

Flow diagram below indicates implemented sensors of various kinds in a LiDAR instrument, as well as the computation steps which form the ground and underwater coordinates.

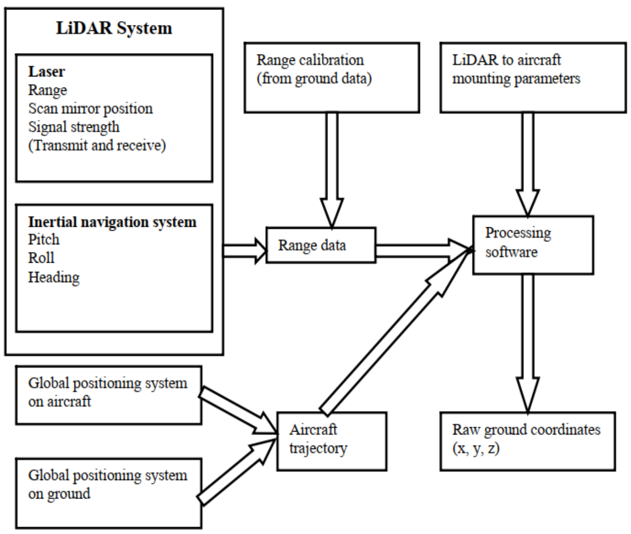

Fig. 3. An illustration of flow diagram used for computation of the ground coordinates [8]

III. AIRBORNE TOPOGRAPHIC LIDAR

Airborne LiDAR System or ALS which stands for Airborne Laser Scanning represent a remote sensing technique used to measure the distance to an object. The basic principle of measuring distance to an object using this type of LiDAR is by determining the time of flight for an emitted laser beam. Basically, a laser pulse is emitted from an aircraft in order to measure the terrain elevation, which is derived from the time between emission and reception of reflected pulses. Then, the x, y, and z coordinates are registered through laser altimetry. Technologies on which LiDAR relies for its operation on are Global Positioning System (GPS) and Inertial Measurement Unit (IMU). The importance of these technologies plays the crucial part in airborne LiDAR scanning because it provides LiDAR with the location and orientation of the remote sensor which is located on the airborne platform. This technique has a special application in shallow waters.

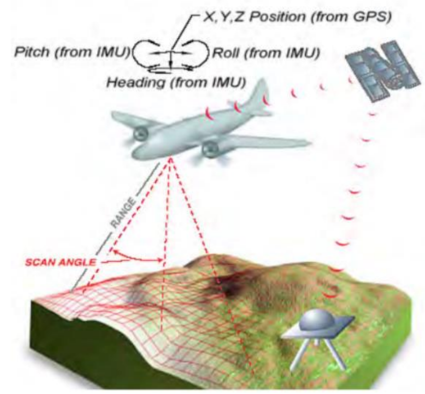

Fig. 4. Airborne LiDAR technology in the process of providing the location of the airborn platform, using a laser beam, GPS and IMU systems [7]

A. *Bathymetric LiDAR*

When there is a need for scanning water bodies or even some ocean traffic points such as bridges, piers, dams and other infrastructure, topographic LiDAR does not complete this task. In order to accomplish sensing of these areas and objects, bathymetric LiDAR is commonly used. The main difference between these two types of LiDAR sensors is that a bathymetric LiDAR has the ability to shoot green laser pulses, while every other component of the bathymetric LiDAR is the same as the topographic one.

The basic principle implies the action of the pulses penetrating the water surface and then returning back to the sensor which is attached to the airborne vehicle. Estimated depth of the water and water bodies is attained by processing the collected data. As it is mentioned already, a laser pulse is transmitted to the water surface, where a portion of the energy is recaptured back to the optical receiver. The remainder of the pulse continues to penetrate to the water bottom through the water column and later, is reflected back to the receiver. Two main factors that defines the maximum depth penetration for a laser are water clarity and bottom reflection. LiDAR can measure various depths from 0.9 m to 40 m with a vertical accuracy of ±15 cm and horizontal accuracy of ±2.5 m, depending on the water clarity. It is important to mention that the elapsed time between the bottom pulses and the received surface allows determination of the water depth.

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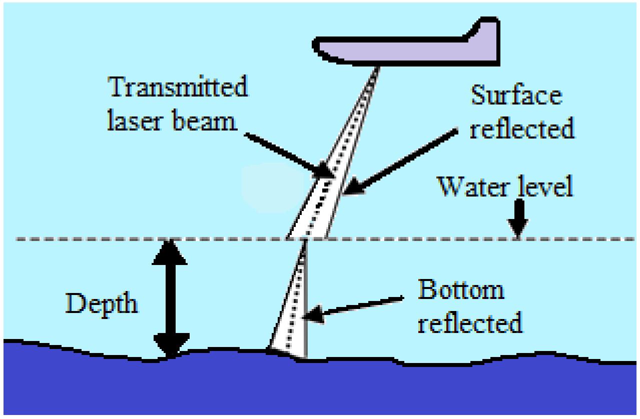

Fig. 5. Basic principle of bathymetric LiDAR [8]

Among all of those parameters mentioned before, water turbidity [18] is the most important one. It is defined as a factor caused by suspended or dissolved particles in water. Those particles scatter light in the water, making it appear cloudy. As far as water penetration is concerned, it is equal to two to three times the Secchi depth [19], which means three times the penetration depth of natural sunlight in a given water column. To be able to compute the water depth, the bottom and surface signals should be clearly distinctive, but in case of shallow depths, these signals overlap. This situation makes determination of the water depth unavailable.

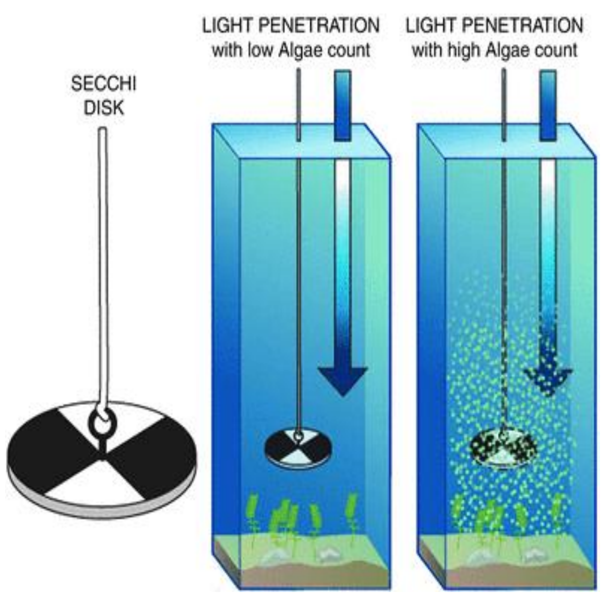

Fig. 7. Display of Secchi disk which is used to measure water clarity [19]

B. Bathymetric LiDAR Sensor Characteristics

When we discuss modern bathymetric LiDAR sensors, it should be noted that it can measure topography in addition to bathymetry, which is a double feature and a great advantage over a traditional topographic LiDAR sensor. It can measure both shallow and deep water systems.

The limit for shallow water is < 10 m and the lower limit for deep water systems is > 10 m. Characteristics of the shallow water systems are a higher measurement frequency, they have a higher resolution, and they have less laser power per pulse and smaller laser footprint diameter. A smaller receiver FOV (field of view) is also characteristic for them and they can only measure water depths within the visible water column. Opposite to this, the deep-water bathymetric LiDAR systems have a lower measurement frequency, low resolution, and they use more laser power per pulse. Also, a larger receiver field of view and a larger laser footprint is used within deep water LiDAR systems.

Depth penetration capability of the laser varies in between 2.0 to 3.0 times the Secchi depth measurement, as it was mentioned before. It is common for survey operators to utilize both sensors for shallow and deep water systems simultaneously, in order to achieve maximal coverage and detail. It is managed by combining those sensors in twin optical port survey aircraft.

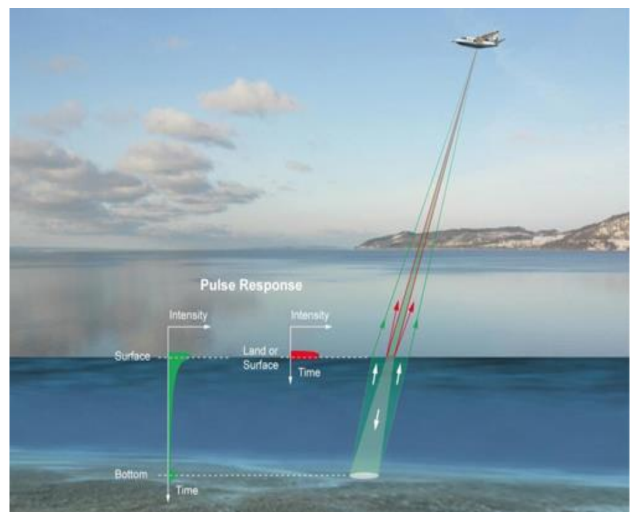

Fig. 6. Illustration of bathymetric LiDAR measurement [17]

We can see that the most important factor when bathymetric LiDAR systems are employed, is its laser energy per pulse, because the laser power represents the strongest influence on depth penetration, when it’s combined with the pulse duration. This is important because the combination of high laser power and pulse duration, can provide us with a result even in deeper water column penetration. All of this mentioned influences a full insonification of the seabed, besides the fact that a high resolution laser’s energy per pulse and low measurement frequency will result in a lower point density.

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C. Advantages and disadvantages of bathymetry

In comparison to methods of topographic data collection such as land surveying, GPS, interferometry, and photogrammetry, LiDAR technology has some great advantages. Over time, LiDAR technology is rapidly improving, as well as its sensors characteristics. Some of them are listed below:

- Higher accuracy and data density
- Fast acquisition and processing
- Minimum human dependence
- Weather/Light independence (not dependent on the sea state)
- Canopy penetration possibilities
- Additional data storage
- High costs
- Fast method (up to 70 km^2 per hour over large linear areas)
- Reflectivity gives information on seafloor characteristics

Also, like every other sensor or detector used nowadays, these sensors have some disadvantages likewise. With that being said, some disadvantages of the LiDAR sensor are:

- Aircraft usage is weather dependent
- Applicable in clear shallow water only
- Less resolution than multibeam unless resolution survey is very high
- Limited penetration in high turbidity areas such as sandy shores
- Hard to use in shallow water depths (< 0.5 m)

IV. ENVIRONMENTAL CONSIDERATIONS

All of the external environmental effects can impact the water column in bathymetric LiDAR measurements. It makes them more sensitive and can lead to data errors, gaps, bad measurement quality and reduced data coverage. It can produce problems and increase cost. Preparations for a successful bathymetric LiDAR survey and measurements, imply numerous factors that needs to be considered in order to minimize unfavorable impacts. These include tides, turbidity, vegetation condition, sea state, ground control accessibility, traffic controls and last but not least weather conditions for flying the aircraft. Important conditions which impact shallow-water laser penetration from bathymetric LiDAR sensors, need to be properly understood and managed before measurement and processing of data. One major hindrance for this process is water clarity, which can either be satisfactory or insufficient. The lack of water clarity can cause great problems for the bathymetric LiDAR sensor. Furthermore, there are other factors that can disrupt the sensor, such as sea grass, low-reflectance and high turbidity.

Considerations of environmental factors and individual characteristics of the system are very important when selection and employment of LiDAR is in focus. Some important attributes and points of a best system for a survey are environment, survey area, sensor availability and project requirements. Point density, coverage, maximum depth, final product requirements and intended purpose for the data are some of the most important aspects that determine the choice of sensor. Even when the choice is the right one, the knowledge and experience of the operator is the key to a successful survey.

V. AUTONOMOUS SHIPPING

Since LiDAR is not very widespread and investigated around the world, so it had recently paved a path towards a better understanding and greater investigation as well as exploration. We are surrounded by deep waters and oceans that are considered as mysterious areas in the manner of exploration, even in the 21st century with all of technological opportunities and achievements.

Exploration of deep oceans is a complex process. Maritime transport requires knowledge of terrestrial parameters, climate change and accurate weather forecasts in order to ensure safe trips. In addition, all of these conditions need to be fulfilled to achieve accurate LiDAR measurements. Protecting marine and coastal environment, bridges and various objects, is considered as one of the more important tasks of this sensor. However, it can serve for the purpose of updating nautical charts, cable landing sites which are connected to undersea fiber communication projects and off-shore wind farms.

Fig. 8. EchoBoat-240 seafloor system [13]

EchoBoat-240 Unmanned Surface Vessel dockside will eventually be demonstrated by Seafloor Systems. It excels in mapping shallow bodies of water. EchoBoat-240 has navigation abilities that led it into the real of fully-autonomous vehicles. A portable multibeam survey vessel will be displayed by the Seafloor System as a new platform which combines heightened portability and high-resolution data quality of a multibeam sonar.

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Predictions assume that LiDAR will be crucial in mapping and monitoring of coastlines which could bring us many new improvements in safety transport, investigation of the seafloor and even in ecology.

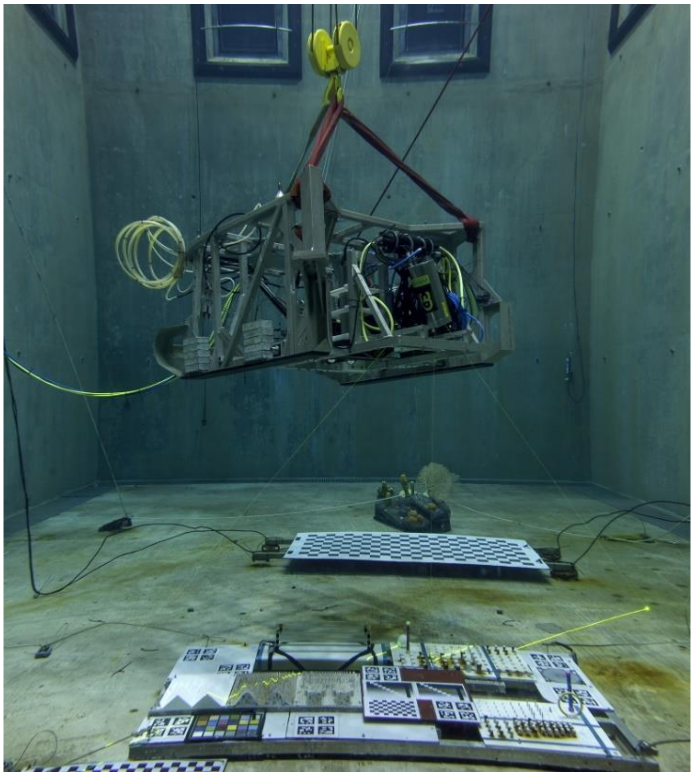

Fig. 9. Wide Swath Subsea LiDAR system in a test tank flown at a low altitude to achieve much higher resolutions than systems imaging from further off the bottom [2]

The Wide Swath Subsea LiDAR sensor, called WiSSL is able of mapping large areas at a 1 cm resolution. Its lasers are capable of pulsing 40,000 times per second in order to produce discrete surroundings. 90 degree vide field of view is made possible due to the WiSSL being equipped with two optical heads. With that being said, it is possible to achieve full bottom coverage at a maximum velocity of 1 m/s. Therefore, it is concluded that WiSSL is the first subsea LiDAR optimized for efficient mapping in the deep ocean [2].

Automated guided vehicles that are capable of providing real-time position data on port infrastructure, people, and objects, have one of the important roles in LiDAR application. The role of LiDAR sensors is to provide and enhance predictability and reliability, being a valuable component to port equipment. It can also improve efficiency and reduce risks and costs in marine transport and seafloor exploration processes.

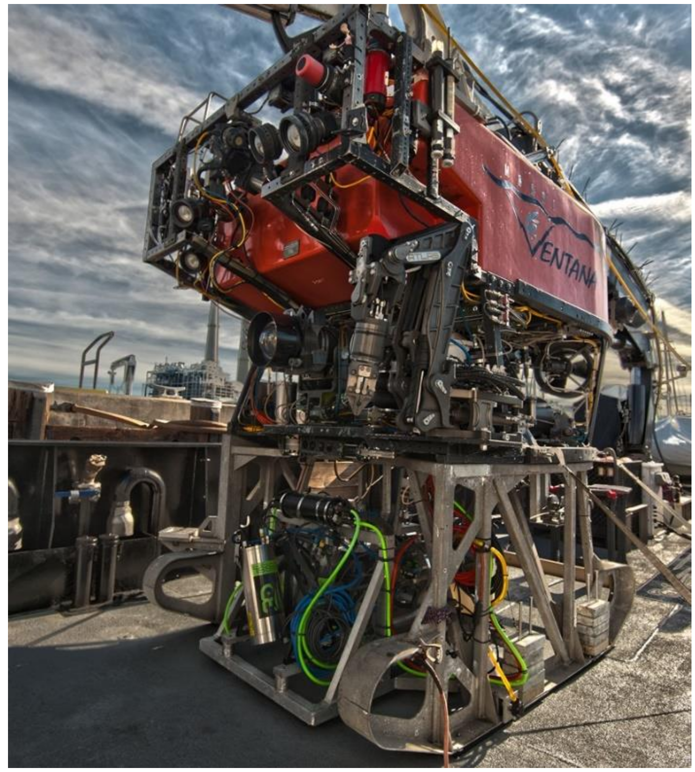

Fig. 10. This photo shows launching the ROV Ventana into the ocean [2]

VI. Current applications in maritime transport

One of the newest applications regarding maritime transport and safety is helicopter-mounted laser that scans and detects underwater mine targets. The US Navy is the first user of this system which brings faster detection and a wider FOV to countermine investigating missions.

LiDAR type that enables high-speed shallow water mine detection and efficient results and data processing, is called Airborne Laser Mine Detection System. When echo is returned to the sensor, the data is collected, and next step is choosing the method of destroying the mine. For example, a detected mine can be either destroyed or brought out and transported to another place safety. Cameras underneath an aircraft are receiving reflections of emitted laser beams, from the water and later, processed reflections produce images that are displayed on an airborne console.

This system can work either in day or at night, regardless of light conditions, and without worrying about submerged equipment. This action can provide identification of objects on the bottom of the ocean and pursue attack with a much lower risk of mine-attack and mine explosion.

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Fig. 11. An illustration of Stanford's photoacoustic airborne sonar system [3]

VII. Conclusion

LiDAR is currently experiencing an expansion. The contribution and value of this technology can change the future in which we will live. Changes in humanity are inevitable if we want to live longer and healthier, as well as save the planet. This sensor can help us succeed in that with its techniques that could provide us with data on inaccessible parts of the planet. Opportunities for research and protection of nature and humankind, transportation development among other things are growing as LiDAR becomes more effective, widespread and autonomous.

In this paper, the emphasis was put on safer maritime traffic and transport, as well as on the research of sea floor and hidden or buried objects. Airborne LiDAR can help improve coastal operations, along with signalling other ships at sea of a potential hazard detected by the sensor. That hazard could be a natural obstacle or perhaps an underwater mine, even a bridge that is not visible at night under some circumstances. Given that climate change is beginning to seriously threathen the planet, contributing towards the battle against climate change is necessary, and this could be achieved with the benefits of Industry 4.0 and novel measurement techniques and analysis.

A future application of this sensor, could be to help in the removal of carbon dioxide from the oceans. Using this technology, we can direct laser beams to determine where heavy seaweed is cultivated and enrich the water with alkaline compounds that would equalize the pH levels. By doing this, we can accelerate the restoration of underwater ecosystems, and remove excess carbon dioxide from water via electrochemical purification. In addition, another potential use can be found in analysis of seafloor and underwater rocks, minerals and various underwater species. One more idea worth mentioning is submarine and hazardous liquid detection, such as oil spills.It would be delightful to see the industry reap the benefits of this development, as that would provide additional valuable information to the end user. It is certain that LiDAR technology is already benefiting from open data, artificial intelligence and machine learning. These advantages should be utilized as much as possible as an overture to the solution for the near future.

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