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REQUIREMENT AND CHALLENGES OF MULTI-SENSOR DATA FUSION

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Abstract

Space has evolved as the fourth domain of warfare and has proven to be a 'game changer' as demonstrated by the recent conflicts. Space-based sensors offer enormous capabilities and possibilities that grow larger every day, and their exploitation is only limited by the users' innovative thought processes. However, the current satellites host only one or at least two sensors on one platform. Each sensor has some strengths and weaknesses. There is a case for hosting more than one sensor on a single platform with a real-time fusion of these, as well as the outputs of multiple single-sensor satellites and even ground-based sensors, to make the best use of the strengths of the sensors. The fusion of sensors will provide a much more precise picture to the commander on the ground, enabling him to make a more accurate and timely decision. The concept of data fusion has existed for some time now. However, fusion of data in real-time has been accentuated by the advent of newer sensors, processing techniques that are more advanced, and better hardware that has improved the quality of processing data. Presently, data fusion systems are being utilised expansively for tracking targets, their identification in an automated fashion, and applications with limited automated reasoning. The commercial market is becoming available with software for data fusion applications. In principle, fusion of multisensory data provides significant advantages over data from a single source. This article discusses the feasibility of multi-sensor data fusion and its advantages and suggests some civil and military applications. It also brings out challenges in multi-sensor data fusion and possible solutions using the latest technologies, such as Artificial Intelligence (AI) and Machine Learning (ML), to overcome these challenges.

INTRODUCTION

The current Russia-Ukraine and Israel-Hamas conflicts have highlighted the need for nations to embark on a rapid race to develop new capabilities. In future conflicts, space-based sensors would be essential for detecting, classifying, identifying, and destroying targets deep inside enemy territory. Surveillance and reconnaissance satellites provide strategic data for intelligence assessments and play a critical role in meeting the rapid response that is the requirement today for national security. The mission of these satellites has grown beyond the strategic sphere to more time-sensitive operational and tactical levels of support, even though intelligence is still a critical component of the mission. Persistence is necessary to meet these demands for quick responses in order to recognise threats that could arise at any moment or from any place, including mobile launchers, ships, submarines, aircraft, and even space.

The remote sensing process involves the use of various imaging systems where the following elements are involved: illumination by the sun or moon; travel through the atmosphere; interactions with the target; recording of energy by the sensor; transmission, absorption, reflection, and emission data for analysis; retrieval, interpretation, and analysis of the signals; and decisions for applications. Multi-sensor data fusion has drawn a lot of interest lately for both military and non-military uses. By combining data from several sensors with relevant information from linked databases, data fusion techniques can produce outcomes with greater precision and increased accuracy than obtained with just one sensor. Multi-sensor data fusion, as a concept, is not new; animals and humans have developed the ability to use multiple senses to improve their survival. Military applications for multi-sensor data fusion include guidance for autonomous vehicles, automated target recognition for intelligent weapons, battlefield surveillance, remote sensing, and automated threat recognition systems, such as identification of friend or foe systems. Fusion of multi-sensor data may increase the accuracy by combining data from the same source and its adding statistical advantage.

A prime example of the advantages of multi-sensor data fusion that is currently in operation is the F-35 fighter aircraft. It has multiple systems with associated sensors, like the airborne interception radar, the Electro-Optical Targeting System (EOTS), the Electro-Optical Distributed Aperture System (DAS), the Electronic Warfare suite that includes sensors like Radar Warning Receiver (RWR), the Communication, Navigation and Identification (CNI) system, etc, the data generated by which is fused together. The aircraft features autonomous sensor management where it also receives data from other friendly airborne and surface-based platforms which is fused on-board the aircraft's fusion engine using advanced computing algorithms. Applying this corollary to space, deploying different sensors, say combination of SIGINT and IMINT sensors, onboard a satellite along with use of AI and edge processing would help enhance situational awareness at strategic level.

PLATFORMS

In addition to ground and airborne sensors, near-space and space sensors are finding more significant applications in sensing. There are three overarching categories that satellites can be divided into: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Orbit, also called Geosynchronous Equatorial Orbit (GEO) satellites. The most common satellites supporting global development are GEO satellites for communications, wildfire mapping and weather monitoring. These satellites orbit the Earth's equator at the same speed from west to east as the planet, which enables them to stay over a certain spot on the planet's surface continuously to capture imagery of its surface and atmosphere. GEO satellites' spatial resolution has been on an improving trend courtesy the technological advancements. The photographs of the Earth captured by sensors on-board LEO satellites at a considerably higher spatial resolution as compared to those by GEO satellites as the former are at much lesser distance to the planet. Another prominent kind of LEO satellites are the north to south moving Polar-orbiting satellites. Sun-synchronous orbit is a particular kind of polar orbit in which when a satellite orbits, it is able to capture the Earth at approximately the same time every day. Near space has become a domain where civil and military platforms find Intelligence, Surveillance and Reconnaissance (ISR) applications at heights from 20 to 50 km. The low perturbation in the weather allows the platform to remain aloft more easily with basic propulsion systems, a better line of sight to the ground is offered, and laser communications allow connectivity, which are the advantages for ISR applications. The High-Altitude Pseudo Satellite (HAPS) drones flying in the stratosphere have provided low-cost solutions and technological advantages compared to LEO satellites, which can stay aloft for 60 to 90 days. These HAPS can provide persistent coverage over the area of choice and can be exploited to cover the gaps, especially to counter the threats from hypersonic weapons. Recently, the US launched the X-37B, and China tested the Shenlong spacecraft, which is capable of delivering and intercepting payloads in space, altering their orbits, and returning to the Earth for refuelling.

ADVANTAGES OF MULTI-SENSOR FUSION

Data fusion is amalgamation of data obtained from multiple sources in order to attain improved information. Data fusion in a multi-sensor environment, by using data from multiple dispersed sources, results in various advantages such as the few enumerated below:

- Higher probability of detection.
- Ambiguity reduction.
- Increase in detection accuracy.
- Reduction in false alarm rate.
- Reduction of heterogeneous errors.
- Lower detection error probability.

- Higher reliability.
- Increased system availability.
- Reduced communication bandwidth.
- Improved all-weather performance.

TRENDS IN MULTI-SENSOR FUSION

Software tools like the Geographic Information Systems (GIS) are crucial in military operations as they translate the database to create, manage and analyse the information spatially on the map. Command, control, communication and coordination concepts in military operations primarily depend on the availability of accurate data and enable fast decision-making. In the present digital era, ISR requirements are near real-time. While there are different sensor technologies for target detection, identification, and classification [Communication Intelligence, Electronic Intelligence, and Imagery Intelligence (COMINT, ELINT, IMINT)], we may not get near real-time actionable technical intelligence unless data from these sensors are fused. Due to technology constraints, each sensor type and platform has advantages and disadvantages. Aerial imagery offers spatial resolution of up to 1-5 cm per pixel. Compared to satellite photos, the field of view covered by an aerial photograph is substantially smaller and more mission or task-specific. Aerial photography is excellent for more localised applications that maximise spatial resolution. Aerial and satellite data share this complementary relationship making the two potent sources of valuable geospatial information. Thus, different sensors detect, identify, and classify other targets (static or moving) with varying resolutions, swaths, and revisits. Different image fusion algorithms may be needed due to the proliferation of space-borne sensors. Another challenge in fusing the real-time data from various sensors is the platform (ground, air and space-based) on which these sensors are installed. In the maritime domain, the moving targets and their data are available at different times and pose a challenge for data fusion. In the current Russia-Ukraine conflict, Palantir's software, which uses Artificial Intelligence (AI) to analyse satellite imagery, open-source data, drone footage, and reports from the ground to present commanders with military options, is "responsible for most of the targeting by the Ukrainians".[1]

The development of remote sensing images in many visual tasks has increased the demand for obtaining images with better precision in details. However, directly providing images rich in spatial, spectral, and temporal information at the same time is not feasible. Combining the information from several photos is one workable technique. Deep learning has made remarkable progress in image processing for fusing remote sensing images at the pixel level. There must be a trade-off among spatial, spectral, and temporal resolution, as these cannot be maximised simultaneously. Trade-offs between the temporal, spatial, and spectral resolutions must be made by a single remote sensor. In order to properly give the various properties of the targets, many modern satellites frequently have two or more different types of sensors. Besides optical images, radar images obtained by Synthetic Aperture Radar (SAR) and Light Detection and Ranging (LiDAR) enhance the detected target's descriptive and expressive ability. While LiDAR measures the time and change in intensity of the laser to travel to and for the target, SAR records the intensity of the radar signal's backscatter. Deep learning is to be used. Compared to optical images, they can provide complementary contextual and structural information, widely used in visual tasks such as cloud removal and mapping.[2] Therefore, there is a need to understand the difference between syntactic understanding and semantic understanding to build a fusion hierarchy.

One feasible solution is to use image fusion technology. The fusion results can fully use complementary information and correlation of multiple images to generate a more comprehensive and accurate interpretation of the same scene than ever before.[3] The best remote sensing method depends on the classification problem's complexity, the available data set, and the goal of the analysis.[4] Multi-sensor data fusion can be carried out at following four processing levels:

- **Signal Level Fusion.** In signal-based fusion, signals from different sensors are combined to create a new signal with an improved signal-to-noise ratio than that of the original signals.[5]
- **Pixel Level Fusion.** Pixel-based fusion is performed on a pixel-by-pixel basis. It generates a fused image in which information associated with each pixel is determined from a set of pixels in source images to improve the performance of image processing tasks such as segmentation.[6]
- **Feature Level Fusion.** Feature-based fusion at the feature level requires extracting objects recognised in the various data sources. Depending on their environment, it involves extracting salient features such as pixel intensities, edges, or textures. These similar features from input images are then fused.[7]
- **Decision Level Fusion.** This consists of merging information at a higher level of abstraction and combining the results from multiple algorithms to yield a final fused decision. Input images are processed individually for information extraction. The obtained information is combined, and decision rules are applied to reinforce common interpretation.[8]

Current Trends. The present trends in multi-sensor data fusion are:

- **Deep Learning for Feature Extraction and Fusion.** Deep learning models (like convolutional neural networks) are revolutionising how features are extracted from diverse sensor data. Instead of hand-crafted features, deep learning involves the most relevant representations directly, improving fusion accuracy and adaptability.
- **Multi-Modal Fusion.** Combining data from significantly different sensor types (e.g., optical, hyperspectral, radar, LiDAR) is a significant focus. This unlocks a much richer understanding of the observed environment.
- **Generative Adversarial Networks (GANs).** GANs are used for tasks like image super-resolution and image translation. This allows the fusion process to generate enhanced data or translate between sensor modalities, improving decision-making.

- **Attention-Based Models.** Attention mechanisms (like transformer architectures) selectively focus on the most critical features from different sensor data streams. This improves the efficiency of data fusion and makes it more robust.
- **Graph-Based Fusion.** Graph Neural Networks (GNNs) characterise the dependencies and relationships between the data points from various sensors. Fusion methods that are more sophisticated are made possible by GNNs, especially for time-series or complex scenes data.
- **Uncertainty Quantification and Explainable AI.** Fusion models can be integrated with uncertainty measures so as to be able to assess the reliability of the result, a crucial requirement for critical applications. Explainable AI techniques help improve the transparency of these complex models.

NOAA'S HAZARD MAPPING SYSTEM (HMS)

The Hazard Mapping System (HMS) is a tool used by the National Oceanic and Atmospheric Administration (NOAA) to detect fires and the smoke emissions produced by them over North America that degrade the quality of air. The system utilises imagery produced by the sensors on-board seven NASA and NOAA satellites operating in geostationary and polar orbits in a singular workstation environment to generate the desired results. The data produced by the geostationary satellites, GOES-11 and GOES-12, has high temporal (15 minutes) but nominal spatial (4 km) resolution. Visible imagery that is used for detection of smoke has a resolution of 1 km. NASA's Terra and Aqua spacecraft in the polar orbits provide host the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument whereas the Advanced Very High Resolution Radiometer (AVHRR) is available on NOAA-15, NOAA-17 and NOAA-18 satellites, again, in polar orbits. This data by polar satellites has a resolution of 1 km for the 3.9µm band but lower temporal resolution. The low and mid latitudes are imaged twice a day by the polar orbiting satellites while locations at higher latitudes have a frequent temporal resolution of up to 6 times a day. The sensors employ automated fire detection algorithms. The analysts incorporate suitable algorithms and control procedures for accepting, adding, discarding and validating fire detection hotspots which is them analysed. The HMS generates forty eight hour smoke forecast aids in air quality forecasting. The HMS also allows integration of other ancillary data with the imagery data in near-real time and continuously updates as newer data keeps becoming available.[9] In this manner, data from different types of sensors with varying temporal and spatial resolutions is fused to exploit the strengths of each one of the sensors while overcoming their individual limitations.

CIVIL APPLICATIONS FOR MULTI-SENSOR FUSION

- **Precision Agriculture.** Multi-sensor fusion of hyperspectral and high-resolution optical imagery can enable precision agriculture by identifying nutrient deficiencies and diseases in crops and crop stress early on. For targeted interventions, structural information of crops can be provided by LiDAR data.
- **Disaster Monitoring and Response.** Pro-active monitoring of natural disasters is possible by amalgamating radar, optical and thermal data which builds up timely situational awareness in case of fires, floods and earthquakes. The usage of radar data enables monitoring in cloudy conditions as well. This pro-active approach would result in much improved rescue efforts and more efficient allocation of resources.
- **Urban Mapping.** LiDAR point clouds fused with optical imagery generate highly detailed 3D urban models, invaluable for urban planning, change detection, and infrastructure monitoring.
- **Environmental Monitoring.** Data fusion enables comprehensive tracking of land-use changes, deforestation, water quality, and biodiversity across multiple sensor types and periods.

MILITARY APPLICATIONS FOR MULTI-SENSOR FUSION

- **Intelligence, Surveillance and Reconnaissance (ISR).** These are the core applications. Fusing imagery and data from various sensors (optical, infrared, radar, hyperspectral, LiDAR) on satellites, drones, and aircraft provides unprecedented situational awareness. The Automatic Identification System (AIS) for maritime tracking is being installed on ISR satellites

- **Troop and Vehicle Movements.** Identifying enemy formations, concealed units, and force build-ups.
- **Infrastructure Detection.** Mapping supply routes, bases, communication facilities, and potential targets.
- **Camouflage Penetration.** Synthetic Aperture Radar (SAR) can pierce some camouflage; infrared and hyperspectral sensors can detect heat signatures or spectral anomalies indicating concealed objects.
- **Target Acquisition and Precision Strikes.** Multi-sensor fusion creates highly accurate targeting data for guided weapon systems.
- **Geolocation Accuracy.** Combining GPS, optical imagery, and terrain data (from LiDAR, for example) delivers precise coordinates for artillery, missiles, or air strikes.
- **Change Detection.** Comparing images over time highlights anomalies for targeting, like new structures or the appearance of high-value targets.
- **Battle Damage Assessment (BDA).** Post-strike analysis using high-resolution imagery and sensor data evaluates the effectiveness of attacks. This informs decisions on re-engagement or target confirmation.

THREAT DETECTION AND COUNTER MEASURES

- **Missile Defence.** Combining radar, infrared, and optical sensors offers enhanced early warning and tracking of ballistic and cruise missiles.
- **Counter-Drone Systems.** Fusing acoustic sensors, radar, and optical data helps detect, identify, and neutralise small drones that pose increasing threats.

TERRAIN MAPPING AND NAVIGATION

- **3D Terrain Models.** LiDAR and photogrammetry create accurate 3D terrain representations for mission planning, identifying choke points, and simulating attack scenarios.

- **Obstacle Avoidance.** Real-time sensor fusion on vehicles and drones enables autonomous navigation and obstacle detection in complex environments.

MULTI-SENSOR FUSION METHODOLOGY

Data collection is the first step. The accuracy of target coordinates' data will assist in integrating the targeting weapon system. Artificial Intelligence (AI) and Machine Learning (ML) require data to train the system. There must be a trade-off among spatial, spectral, and temporal resolution, as they cannot be maximised simultaneously. Deep learning is to be used. For example, hyperspectral imaging is the best way to handle camouflage. The data set for strategic targets like a silo of Intercontinental Ballistic Missiles (ICBMs) is not readily available for ML. Therefore, there should be mechanisms to generate synthetic data. To build a fusion hierarchy, there is a need to differentiate between syntactic and semantic understanding. Fusion algorithms like high pass filtering, Intensity-Hue-Saturation (IHS), multi-resolution analysis-based methods, Principal Component Analysis (PCA), different arithmetic combinations (e.g., Brovey transform) and artificial neural networks are some of the algorithms used for remote sensing. Each fusion method offers its own advantages and suffers from its limitations. Clouds offer benefits in speed, scale, and flexibility. They also help with "data fusion"—combining different pieces of information to reveal things one source cannot capture, including things no human would think of looking for.[10] Resilience helps systems to remain adaptable and flexible to ad hoc changes and resistant to failures without loss of performance.

Some of the examples of sensor fusion are:

- **Hyperspectral + SAR**. Hyperspectral imagery reveals objects' 'chemical fingerprints', identifying materials used in camouflage or weapons manufacture. By seeing through clouds and some foliage, SAR confirms the locations of these potential targets.
- **Optical + Infrared + Radar**. Optical imagery provides high-resolution visual detail. Infrared detects heat signatures from vehicles and activity.

Radar can see through adverse weather conditions or even provide ground penetration capabilities. Fusing these delivers a clearer picture, by day or night, in rain or sunshine.

- **Signals Intelligence (SIGINT) + Geospatial Data**. Geotagged SIGINT data (like intercepted communications) fused with satellite or drone imagery can reveal the disposition of enemy forces or the origin of hostile transmissions.

CHALLENGES IN MULTI-SENSOR DATA FUSION

Data fusion based on multiple sensors hosted on ground and aerial platforms is a reality today. However, space-based platforms still host mostly single sensors [Electro-Optical (EO), SAR, COMINT, ELINT, etc.], and data fusion in near real-time from different sensors is a challenge due to the non-availability of varying sensor data simultaneously. By repeatedly returning to the same region of the Earth, satellites are able to give great temporal resolution over vast regions of the surface. A satellite can constantly collect data for the length of its lifespan (for decades), thereby, making the imagery valuable and cost-effective for use cases like detecting changes and monitoring on a large scale. Considering the advantages of space-based sensors, most advanced armed forces have deployed multiple single-sensor satellites in different orbits and inclinations to achieve near real-time ISR capabilities in their area of interest at considerable cost. The concept of 'Tip and Cue' has evolved to achieve near real-time ISR with single-sensor systems. At the same time, SIGINT satellites provide the tip for subsequent cues by the high-resolution EO/SAR sensors for detection, identification, and classification.

Deploying multiple sensors on identical spacecraft is the need of the hour for near real-time persistent ISR. A consortium of private companies, including GalaxEye, Ananth Technologies, and XDLINX Labs, has initiated a SAR and optical payload project on-board a single satellite, which will likely be launched in 2024.[11] Apart from hosting the various sensors on the spacecraft, there is also a need to develop high-speed on-board processing capabilities and data fusion algorithms and establish Earth stations spread across the globe connected on high-speed data downlinks for near real-time ISR capabilities. Communication satellites placed in geosynchronous orbit are increasingly broadcasting high-power digital signals. They can be used for passive bistatic geosynchronous radar applications by adding an appropriate receiver to another satellite. Such a receiver will sense the scattered signals of the transmitter, and if in sync, will form SAR images of the target. Ground-based bistatic receivers can also help track targets using space transmissions and ground and air assets of commercial and military broadcasts. While the need for correlating and collating the data and information received from the various types of sensors described earlier is indisputably justified, the task is more complex and uphill than appears at first glance.[12] The challenges in integrating the information are also of several types and originate from various contexts. Some of these are enumerated below:

- Data quality and calibration. Misalignment, noise, and resolution differences between sensors remain key challenges. Preprocessing and sensor calibration are essential. The five Vs of data are volume, velocity, veracity, variability, and variety. They are derived from big data systems but often, sensors produce large volumes of data sent at high speed through network links, the veracity of which must be checked, which might vary over time and contain a wide variety of data types from various sub-systems. The task of optimising satellite communications can be done by using AI.[13]
- Integrity as a property ensures accuracy and comprehensiveness of the system where multiple nodes are operating in each system. Resilience helps systems to remain adaptable and flexible to ad hoc changes and resistant to failures without loss of performance.
- Scalability to big data. Large-scale fusion demands efficient algorithms that can handle the increasing volume and variety of remote sensing data sources. Modularity is a property where smaller components are combined to form large systems. These modular components should be

such that they can be removed or replaced without any disturbance to the system's operation.

- Data accessibility. Promoting open data policies and cloud-based solutions will democratise multi-sensor fusion research and applications.
- Non-standard data formats are used by different Original Equipment Manufacturers (OEMs). Sensor data conflicts arise from different accuracies and reliabilities of the deployed sensors.
- Non-homogenous data increases false alarms. For example, one aircraft detected by different radars might be presented as multiple aircraft on an integrated screen.
- Requirement of high level of customisation because of a wide variety of sensors.
- A more significant challenge for customising space-based sensors as compared to terrestrial sensors.
- Challenges of integrating near-real-time data. The capability of a system to perform computation in real-time when an external process occurs so that those results can be made use of to control, monitor, and respond to, the process.
- Copyrighted algorithms used by OEMs in sensor handling.
- Non-maturity of indigenous data fusion and integration algorithms.
- Use of AI applications to interpret and fuse a large volume of images / videos at a centralised data processing facility.

MILITARY APPLICATION CHALLENGES

- **Formulation of Joint Space Doctrine.** There is a need to evolve the procedure for the formulation of a Military Space Doctrine and place it in the open domain for use by the civil-military industrial complex. It will pave the way for those involved in research, development, innovation, safe operations, and maintenance of systems. After the doctrine is released, it will be a precursor for the Military Space Strategy to provide the right direction to the stakeholders. Following the existing international treaties, the strategy will bring solutions to enforce net-centric ISR.

- **Defense against Non-Kinetic Weapons.** The Outer Space Treaty of 1967 bans territorial claims on celestial bodies and the stationing of nuclear weapons in space, but it is silent on conventional weapons. Other threats include ground-based "directed energy" weapons: lasers, high-power microwaves, and radio-frequency jammers.
- **Data handling and processing speed.** Massive amounts of raw sensor data pose challenges. On-board pre-processing and robust computing infrastructure are needed for real-time analysis.
- **Artificial intelligence.** Employing AI and ML for automated object recognition, threat analysis, and optimised sensor deployment will be essential. That is, while AI and ML are exploited to analyse the information and deliver solutions, they also need be used for automated threat detection, mitigation and response against cyber-attacks for protection of critical information, systems and infrastructure. Developing ML algorithms for cyber security of own networks and systems would make them more robust by enabling them to work in real-time.
- **Sensor miniaturisation.** Smaller, more powerful sensors enable deployment on a broader array of platforms, especially small drones, for tactical battlefield awareness.
- **Defense against Cyberattacks.** Data security and resilience fusion systems must be robust against cyberattacks, jamming, and deception, as adversaries will also employ advanced counter measures.

CONCLUSION

Space, the fourth domain of warfare, is the new frontier which has emerged as a "game changer" in war. Space control has become as important as land, sea, and air dominance and is increasingly congested, contested, and competitive. Space technology makes military forces in all other domains more powerful. ISR satellites offer nations a "persistent stare capability" that makes battlespace transparency possible through practical ISR. The SIGINT (ELINT and COMINT) satellites help monitor the enemy's radar transmissions and communications. The electro-optical, synthetic aperture radar and infrared capabilities help accurately locate the targets in real-time. Military forces use GIS in various ways, including cartography, terrain analysis, intelligence, battlefield management, remote sensing, and military installation management. There is a need to have satellites carrying multiple payloads of ISR. A start-up in India has recently taken one such step. In addition, the fusion of data monitored by various sensors mounted on numerous platforms must be undertaken to ensure accurate data is correlated. Developing software and AI tools will enable a better appreciation of the situation. The promulgation of the Space Doctrine and Strategy will pave the way for the optimal utilisation of civil-military assets.

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