VOTERS: Design of a Mobile Multi-Modal Multi-Sensor System

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ABSTRACT

The US roadways and bridge decks require an estimated $2.2T in investments to improve from its current *D* score in the most recent ASCE report card [29] to a good level. A network-wide health assessment of the roadway infrastructure is necessary to direct investments to the areas of most need and benefit. However, current survey methods are too expensive in terms of man power and impact to traffic.

This paper introduces the Versatile Onboard Traffic-Embedded Roaming Sensors (VOTERS) project which provides a framework to complement periodical localized inspections of roadways and bridge decks with continuous network-wide health monitoring. VOTERS has created a prototype mobile multi-modal (acoustic, electromagnetic, optical) multi-sensor system compatible with this framework and the goal to help prioritize direct investments to the areas of most need and benefit [9].

VOTERS utilizes traffic-embedded Vehicles Of Opportunity (VOOs) which roam through daily traffic for data collection. This non-intrusive collection eliminates hazardous, congestion-prone work zones, that are typically set up to gather these critical inspection data sets. VOTERS provides maintenance decision makers and researchers with a temporal and spatial data set not available in roadway and bridge deck inspection today. This paper overviews system-level aspects of the VOTERS design, highlights the variety of data collected, and outlines data processing approaches.

General Terms

Performance, Design, Reliability

Keywords

Design, Data streams, Mobile Sensing, Multi-sensor

1. INTRODUCTION

Civil infrastructure construction and maintenance represent a large societal investment. Despite being the lifeline of commerce, civil infrastructure is just at the beginning of benefiting from the latest advances in sensor technologies. According to the latest ASCE report card [29] the United States' (US) infrastructure scores only a D and it is estimated that $2.2 Trilion in investments are needed over 5 years to bring the condition of the nation's infrastructure up to a good condition.

There are four million miles of roads and nearly 600,000 bridges in the U.S. [1] requiring a broad range of maintenance activities. The ASCE report card [29] gives bridges a grade C commenting that "More than 26%, or one in four, of our nation's bridges is either structurally deficient or functionally obsolete. While some progress has been made in recent years to reduce the number of deficient and obsolete bridges in rural areas, the number in urban areas is rising. A $17 billion annual investment is needed to substantially improve current bridge conditions. Currently, only $10.5 billion is spent annually on the construction and maintenance of bridges."

The same report gives roads only a grade of D- commenting that "Americans spend 4.2 billion hours a year stuck in traffic at a cost to the economy of $78.2 billion, or $710 per motorist. Poor conditions cost motorists $67 billion a year in repairs and operating costs. One-third of America's major roads are in poor or mediocre condition and 45% of major urban highways are congested. Current spending of $70.3 billion per year for highway capital improvements is well below the estimated $186 billion needed annually to substantially improve conditions." The [29] estimates that an investment of $930 billion is needed over 5 years to bring up bridges and roads to an acceptable level.

The US faces a monumental problem of infrastructure management in the scheduling and implementation of maintenance and repair operations, and in the prioritization of expenditures within budgetary constraints. The efficient and effective performance of these operations is crucial to ensuring roadway safety, preventing catastrophic failures, and promoting economic growth. Roadway work zones used for assessment and repair are a major source of traffic congestion, which results in lost productivity and wasted fuel. It is a critical need to make the right roadway and bridge deck repairs in the right place and at the right time. However, current inspection methods and strategies (see Section 2.2) used to characterize roadway and bridge deck conditions are not well suited to fulfill this need, because they typically only inspect small localized areas, only periodically (order of years if at all), and mainly through visual (surface) inspection.

In this paper, introduces a mobile multi-modal multi-sensor system that includes a number of vehicles of opportunity which continuously monitor the network-wide health of roadways and bridge decks in an economic way. With the vehicle roaming embedded in the regular traffic, a continues and non-disruptive measurement becomes feasible. The collected data is geo-spatially and temporally correlated at a central location and provides invaluable information

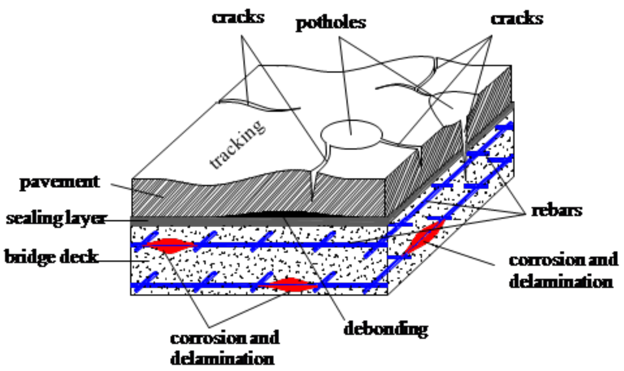

Figure 1: Some common defects and deteriorations found in concrete bridge decks with asphalt pavement overlay

for timely infrastructure investment decisions.

This paper is organized as follows. Section 2 briefly overviews essential roadway and bride defects as well as their health monitoring means. Section 3 introduces the proposed framework with its sensors (Section 3.1), communication architecture (Section 3.2), fusion of multi-modal data (Section 3.3) and bulk data handling (Section 3.4). Section 4 outlines the current achievements with the framework and Section 5 concludes this paper.

2. BACKGROUND

2.1 Roadway and bridge deck defects

Bridge deck and pavement deterioration frequently takes place below the surface and cannot be evaluated by visual means (Fig. 1). Concrete deck deterioration includes delamination arising from chloride induced rebar corrosion, cracking caused by alkali silica reaction (ASR), and cracking caused by overloading or excessive vibration. Pavement deteriorates due to internal moisture damage, debonding, and loss of subsurface support. Reinforced concrete (RC) or prestressed concrete (PC) bridge decks are often overlaid with an asphalt concrete or Portland cement concrete. The presence of the overlay makes it more difficult to detect the subsurface deterioration, and the overlay can also develop damage due to debonding. Pavement layers are subjected to extensive abrasion and deterioration from service loading (e.g. traffic) and environmental attacks (e.g. freeze-thaw, rain, road salts), and thus are subject to deterioration.

Common types of roadway damage are transverse cracks, longitudinal cracks, tracking, corrugation, potholes, delamination, and seepage. Transverse cracks occur more often than longitudinal cracks and can start with a fine crack of less than 0.5 mm in width and of less than 2 cm in depth. Such cracks are hardly visible when it is sunny, but are visible after rain due to the vaporization of the surface water that leaves water in the cracks. Small cracks need to be treated to prevent them from developing into larger cracks. Large cracks often have widths of more than 1 mm, depths of 5 cm, and run meters in length. If large cracks are not sealed, delamination and scaling will follow. If the adhesion between pavement and concrete deck decreases, the overlay may debond from the deck's top surface. The loss of adhesion may be caused by seepage from cracks or potholes. Local debonding may span only several square centimeters and can be difficult to detect because the pavement surface remains intact. Large area delaminations may develop into large cracks at the pavement surface and eventually cause large potholes and loss of pavement. Feedback effects can complicate and accelerate damage progression. Cracks and potholes are often accompanied by seepage. Water enters into the overlay through cracks. The adhesion between asphalt and concrete deck is extremely vulnerable to water penetration. Water within cracks of a pavement will stay and seep. This is most harmful to asphalt pavement.

2.2 Current Inspection Methods

Traditional bridge deck inspection methods, such as chain drag [2], half-cell potentials [4], and chloride contents [3] are slow, require traffic delay causing road closures, and are often not effective. Higher speed technologies such as Ground Penetrating Radar (GPR), infrared thermography, and scanning impact-echo have been developed and used to some extent by highway agencies to meet their needs for bridge deck condition assessment [22, 17, 20, 6, 21]. These technologies suffer either from the need for traffic closures or provide insufficient spatial data coverage, which has reduced their acceptance and reliability.

More modern roadway and bridge deck inspection technologies are vehicle based. They range from profile based single or dual channel air-coupled GPR [23] and Fallen Weight Deflectometers (FWD) to vehicles with lane-wide digital surface (e.g. video, LIDAR) and subsurface (e.g. GPR array) condition survey systems. Most of the currently commercially available systems can be operated within the normal traffic flow, but are only used for inspections of localized areas with no repeat measurements in mind. A need for improved roadway and bridge deck inspection methods and devices using low-cost, faster, and easy to deploy sensor technology remains. In addition a need to manage and jointly consider data from multiple service providers, locations, and inspections dates is highly desired.

3. VOTERS SYSTEM OVERVIEW

The VOTERS (*Versatile Onboard Traffic-Embedded Roaming Sensors*) project (www.neu.edu/voters) provides a framework to complement periodical localized inspections of roadways and bridge decks (as described in section 2.2) with continuous network-wide health monitoring [9]. In order to enable continues monitoring, VOTERS uses a set of sensors mounted on a fleet of vehicles called Vehicles Of Opportunity (VOOs). VOOs are traffic-embedded, i.e. they will roam through daily traffic while collecting data. This eliminates hazardous, congestion-prone work zones, that are typically set up to gather these critical inspection data sets. At the same time, utilizing VOOs for collection improves the safety for the driving public and inspection personnel. Most importantly, by using traffic-embedded VOOs opens the opportunity to much more frequently monitor larger stretches of the roadway infrastructure, which provides maintenance decision makers and researchers with a temporal and spatial data set not availalble with current inspection methods.

VOOs are considered mobile roaming sensor platforms that are driving around a city or other area and at the same time collecting inspection information as a by-product. Taxis, buses, postal service vehicles, city or private vehicles, transportation or other fleet vehicles are all good candidates to be VOOs. Each of them would be equipped with an autonomous multi-modal multi-sensor (acoustic, electromagnetic, and optical) VOTERS sensing system (3.1), which only requires power from the host vehicle. Each VOTERS system will be in communication with a control center via a wireless communication link (3.2) while collecting data. Once returned to operation base, bulk collected data will be transferred via a higher speed communication link, such as 802.11n.

This framework allows the collection of sensor data at traffic speeds that contain roadways and bridge decks surface and subsurface condition information. Over time the VOOs will achieve a continuous network-wide health monitoring of roadways and bridge decks. One key element is the accurate registration of all data streams in time and space (Section 3.3). The collected and/or onboard processed data will be transferred to the control center for further analysis, visualization and decision making, i.e. prioritizing areas to be repaired. An important additional benefit will be the creation of time-lapse data sets that allow the monitoring and analysis of the deterioration process over time, thereby providing experimental results that can be compared with and used to improve existing life-cycle models [13, 32, 34].

The success of this concept will rely on the VOTERS sensing system being economical, light-weight, compact packaging, and non-interfering with the normal operation of the VOOs. It further depends on smart algorithms that can reduce the amount of data to be transfered from the VOOs to the control center at various levels throughout the system (3.4), because the bandwidth of current cellular technology is insufficient or cost-prohibitive for the large amount of data collected.

3.1 Multi-Modal Sensing

VOTERS has developed four new prototype sensing systems that collect data containing surface and subsurface (maximum of 1m deep) condition information of roadways and bridge decks to locate and map defects at traffic speed and is currently testing their performance. The prototype sensing system contains several multi-sensor systems in the acoustic, optical, and electromagnetic domains:

- Acoustic technology that uses tire-induced vibrations and sound waves to determine surface texture and subsurface defects like debonded asphalt layers. [10]
- Improved air-coupled GPR array technology that will map subsurface defects such as corroded rebar, trapped moisture, voids, and the pavement layers (thicknesses and electromagnetic properties). [27, 28]
- Millimeter-wave radar technology (24 GHz) for the near-surface inspection of roadways and bridge decks focusing on pavement condition change detection and surface features covering the roadway such as ice, water, or oil. [33]
- Video technology used to capture surface defects and automatically analyze any increase in defects over time. [14]

Prototypes of these sensor systems have been developed and deployed on the VOTERS prototype vehicle. Their design, specifications, and functionality are described in the references given above. Here the focus is on the types of data collected, how the data relates to the roadway and bridge deck defects we want to map, how their large size influenced the system design and architecture, and how they are routed through the VOTERS system.

3.1.1 Data Types

In this multi-modal sensor system special consideration has to be given to the type of data that is collected by the sensor system/domain. The type influences potential processing and storage requirements. Fig. 2 visualizes examples sources for the data types considered in the framework.

The simplest data type is a single data point per location x and time t. The spatial and temporal interval to the next data point depends on the trigger mode (distance or time) of the system and can vary. An example of such a data stream is the amplitude of the millimeter-wave radar (Fig. 2(d)). Initial processing can be as simple as using a threshold or change detection, but also windowing, transformation to the frequency domain and looking for a pattern in a finite subset of such a data stream.

Another data type is a continuously sampled sensor (time triggered only), e.g. a microphone that collects acoustic waves (Fig. 2(c)). A common way to process such data is to transform them into the frequency domain to perform an analysis or do a principle component analysis. In order to detect the differences between two frequency curves in Fig. 2(c), one solution is to create a feature vector for each sample set using appropriate sampling strategies (e.g. uniform distributed sampling) to represent the data.

A third data type is the collection of a finite length time series at distance triggered intervals (trace), e.g. as the GPR array sensor system (Fig. 2(b)). GPR traces can be analyzed in one dimension through change detection from one trace to the next or by quickly inverting them for the underlying model (e.g., thickness d_i and electromagnetic properties of the roadway layers: Conductivity σ_i and dielectric constant ε_i). A collection of GPR traces can also be simulated [7, 8, 30, 31] and processed in two dimensions, looking for patterns in the x-t images with a variety of pattern recognition methods including Artificial Neural Networks [5, 12, 18, 25].

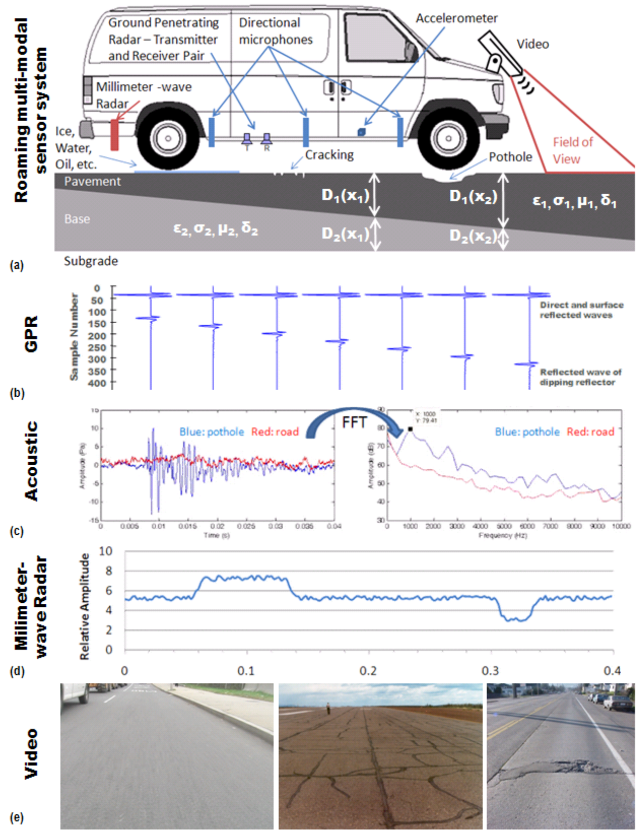

Figure 2: (a) Schematic of VOTERS roaming sensor system (van) equipped with an access point and multi-modal sensor systems. They collect data streams sensing roadways for surface and subsurface defects, layer thickness', and properties. Four different types of data (3.1.1) are collected: (b) GPR traces, (c) acoustic waves, (d) millimeter-wave radar, and (e) video images.

Video or image data (2D arrays) capturing a defined field of view is the fourth data type (Fig. 2(e)). Here, image processing algorithms can be applied to detect cracks [14].

3.1.2 Data Amounts

While a VOO is roaming through the traffic and collecting data, the raw collected data needs to be stored on the vehicle. Once returned to the vehicle base, the raw data will be uploaded to a central location for further processing. This section gives an overview of the data rates to be expected. A fully equipped VOTERS sensing system will collect sensor data from 5 different domains. Table 1 shows the data rates for these sensors.

Two sensors, the GPR array and the video data streams will be distance triggered and make up the bulk of the data. Acoustic microphones, dynamic tire pressure sensor, and the millimeter-wave radar are time triggered. They collect at a sampling rate of 25 μs using a worst-case scenario, which still leads to much smaller data rates. The collection of positioning data is negligible compared to the main sensor systems. In total, 781 gigabytes are expected per hour when driving at 100 km/h.

Table 1: Worst-case scenario of data rates per hour for VOTERS sensing system, assuming a maximum velocity of 100 km/h for the distance triggered systems.

Sensor	Max Sensor	Min Trigger Interval	Points / Sensor / Trigger	Size / point [byte]	Data rate [GB/h]
GPR array	16	0.01 m	1024	2	305.2
Acoustic Microphones	4	25 us	1	4	2.1
Dynamic Tire Pressure	2	25 us	1	4	1.1
Millimeter-wave radar	10	25 us	1	4	5.4
Video Images	1	1 m	5018400	1	467.4
Positioning data	1	0.2 s	4	4	0.0003
				Total	**781.1**

3.2 Multi-Tier Communication Architecture

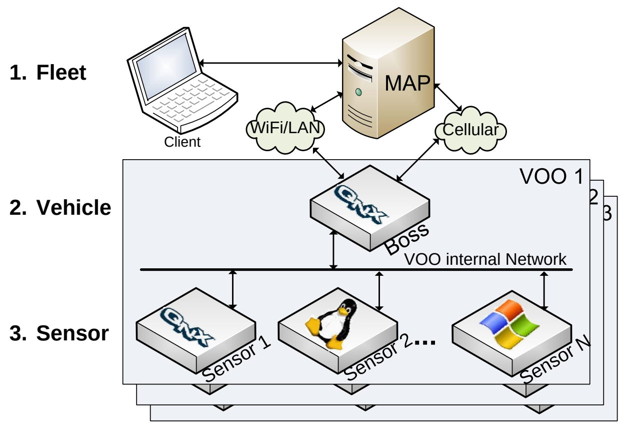

Figure 3: Multi-Tiered Communication Architecture

Fig. 3 shows our three tiered communication architecture. The overall VOTERS system can be thought of as a three tier structure as shown in Fig. 3. At Tier 1 the fleet of vehicles is managed by the a centralized control center, called Management And Prognosis system (MAP). It is responsible for data storage, data management, data analysis and data visualization. The MAP at Tier 1 manages multiple VOOs which are at Tier 2. Each VOO at Tier 2 is represented by a VOO controller called BOSS. The BOSS in turn manages multiple sensor subsystems, which are the third tier in our system architecture.

Each tier has very different communication software requirements as well as hardware implementations. In addition, many different operating systems and heterogeneous networks layers coexist in the system. As shown in Fig. 3, the BOSS (main controller on the VOO) can be running the QNX operating system, while sensor subsystems may run any combination of QNX, Linux, or Windows.

The fleet manager or MAP has two main tasks, first to manage the fleet of VOOs and second to manage and provide access to all collected data sets. The MAP is a geospatial database system that serves as a portal for VOTERS system end-users to access and review roadway condition information. It is designed to allow users to visualize their datasets and results in an intuitive, web-enabled geo-referenced interface that supports their ability to make well-informed decisions. The communication between the clients and server are handled by the ArcGIS server software [11] and clients connect to it via customized web applications, e.g. Silverlight.

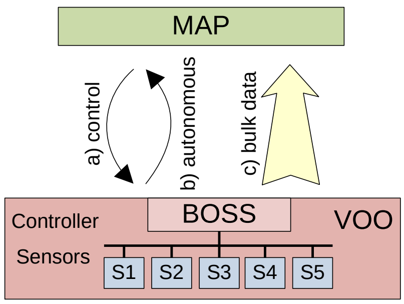

Figure 4: Communication Message Types

Fig. 4 shows the basic message types in the system. There are three types of messages that need to be communicated between the MAP (control center) and the BOSS (VOO controller). First the MAP needs to be able to have two-way communications with the BOSS to for control messages and acknowledgment, request of status updates, data snapshots, and to reconfigure the sensor systems on the VOO. Second autonomous messages sent from the VOO to the MAP need to be received and processed, e.g. location beacon, warnings based on on-board data analysis, and performance problems on the VOO. The third communication type handles the bulk data upload from the VOO and its sensor subsystems to the MAP, which has to be fully automated due to the amount of data and number of VOOs.

As one advantage of the multi-tiered architecture, responsibilities are distributed among levels. The MAP only communicates with the BOSS on the VOO. Any further communication inside the vehicle originates from the BOSS. This separates the responsibilities within the system thus simplifies design and implementation as the MAP can be agnostic upon the vehicle's composition. It also enhances the autonomy for the VOO. It can potentially operate without constant interaction with the fleet manager.

Design and implementation of the a communication framework supporting the above defined principles faces many challenges. A wide range of control messages of different types and content have to be supported over a heterogeneous (different operating systems) structure. At the same time, competing demands of highly varying but low volume control messages, and bulk data messages with low variance but extremely high volumes (see Section 3.1.2) have to be supported.

The VOTERS system addresses these challenges in a composition of (a) object oriented design principles that aid abstracting common functionality, (b) utilizing distributed systems middleware for control messages, and dedicated file transfer protocol (FTP) for bulk data transfers.

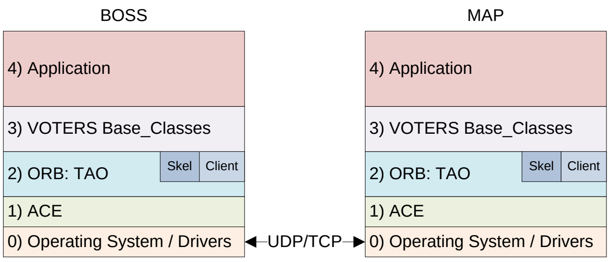

Figure 5: VOTERS Software Stack

Fig. 5 shows the software application stack for the VOTERS system. At its bottom (0), the operating system (QNX, Linux, Windows) provides basic access to the network interfaces with UDP/TCP and FTP protocols. On top of that ACE [16] provides multi-tasking and timing primitives in an OS abstracted fashion. At the heart of the VOTERS system is CORBA [26] implementation TAO [15]. It provides object oriented remote communication allowing for easy construction of distributed systems. A local call (to a *client*) on one machine will be translated in one or more network messages that, transferred to a different machine, will invoke a server (who implements a *skeleton*). On top of TAO, the VOTERS Base Classes provide common implementations across all subsystems, such as status management, provisioning and debug. Finally, the application on top only implements the system specific aspects, such as configuration or management of individual sensors. Utilizing a common software stack across all nodes in the distributed system makes the VOTERS system easier scalable and maintainable.

3.3 Enabling Sensor Fusion

The sensor systems are spatially distributed on the VOO and may have all very different triggering requirements or varying sampling intervals/spacings. Each sensor subsystem may be operated from a separate single board computer. The challenge is to design a system that allows for each data point to be geolocated as accurate as possible to allow for spatial and temporal comparison of different data sets (domains) from one VOO.

It is of critical importance to assign an accurate position to each data point. To achieve this, we rely on two facts (a) the position of sensors relative to the VOO is known and (b) a tight time synchronization is in place. Then, we time stamp every data point collected at each sensor, as well as the positioning data stream recording the location of the vehicle. Then, the correlation between the sensor streams can be computed time delayed.

The synchronization of the sensor data streams with the positioning data requires the following features:

- Each VOO must have an accurate on-board positioning system. In our case we fuse a decimeter accuracy GPS, a Distance Measurement Instrument (DMI) and an Inertial Measurement Unit (IMU) to achieve this requirement.

- Each VOO must have an accurate world time. In our case this is accomplished with a GPS timing board.

- All SBCs on a VOO need to be time synchronized within a certain tolerance (Section 3.3.1).

- All VOOs need to be time synchronized to the MAP within a certain tolerance (Section 3.3.1).

- The location of each sensor on a VOO must be know with respect to the local positioning system (Section 3.3.2).

3.3.1 *Timing Synchronization*

The VOTERS system is designed to collect data at speeds up to $V_{max} = 100$ km/h. The desired spatial correlation between two sensors in post processing is $s_{CorrDelta} = 1$cm. Since streams are correlated via time stamps, this drives the need for the accuracy of time stamping the collected data:

$$t_{StampDeltaMax} = \frac{s_{CorrDelta}}{V_{max}} \quad (1)$$
$$= \frac{0.01m}{100km/h} \quad (2)$$
$$= 359\mu s \quad (3)$$

Considering the desired spatial correlation between streams of $s_{CorrDelta} = 1$ cm and the maximum vehicle speed during recording $V_{max} = 100$, the jitter in time stamping data must not be larger than $t_{StampDeltaMax} = 359$ μs.

Multiple errors play into the $t_{StampDeltaMax}$, e.g. the error in timing synchronization between systems in a VOO and the timeliness of time stamping the data after it has been collected. In order to achieve the desired $t_{StampDeltaMax}$, a time synchronization accuracy in the lower μs between subsystems of a VOO is required. Note that other subsystems may have a lower resolution and less stringent final spatial correlation requirements. Thus the system can allow for a second timing synchronization schemes.

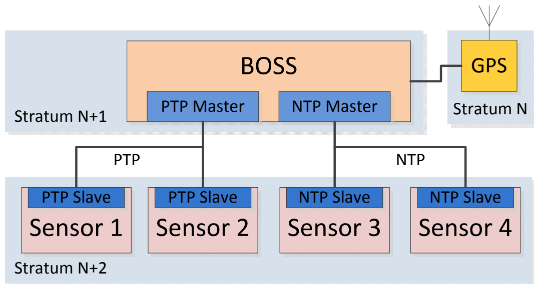

Figure 6: Software-based Timing Synchronization

The first step is that the BOSS acquires an accurate world time from the GPS receiver timing board (Fig. 6), which becomes the common VOO time. There are only very lose requirements on the accuracy of the global synchronization it is only used to correlate the date of time of recordings between vehicles. Conversely, strict timing requirements (359 μs) exist for distributing the vehicle global time to all sensor subsystems. In this case, a common time is essential for correlating sensor data from different subsystems. To accomplish this we evaluated two timing protocols: Network Timing Protocols (NTP) [24] and Precision Timing Protocols (PTP) [19].

Results of the testing of the software based time synchronization are shown in Fig. 7. Using PTP (V1) we observed a maximum jitter of 12 μs with a standard deviation of 2.0375 μs, small enough to achieve our triggering and time stamping requirements.

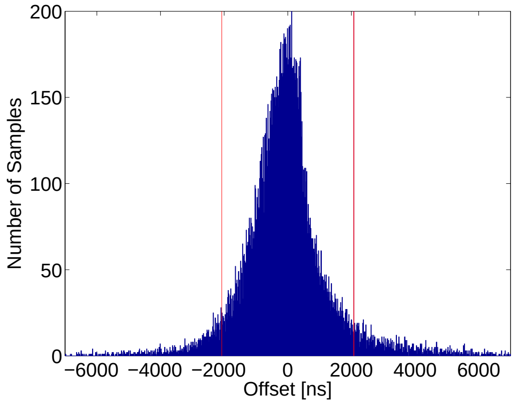

Figure 7: Results of Software-based Timing Synchronization

3.3.2 Sensor Location Calibration

All sensors on a single VOO are spatially distributed (Fig. 2). Since we synchronize all sensor data streams including the positioning data stream by accurate time stamping (3.3.1) we need to correct for their actual locations in relationship to the positioning system, more specific to the location of the GPS antenna.

This is accomplished by first defining the GPS antenna location on a VOO as the local coordinate system origin. Then we record the relative (x, y, z) location of each sensor in a geometry file during the physical installation of the sensors on the VOO. Now the geospatial location of each sensor can calculate by first pulling the global position of the GPS antenna through the time synchronization of both sensor subsystems and then applying the local offset.

3.4 Flexible Data Processing

Having large data streams collecting TB of data per day per VOO (Table 1) combined with the limited bandwidth of todays cellular networks prohibits the option of uploading all raw data to the MAP while the VOO is roaming around collecting data. For the prototype stage of the project and system the data will be uploaded to the MAP while the VOO is parked over night via a wireless or wired Ethernet connection. Now the MAP can start post-processing the data. There are multiple levels of processing possible (Table 2), which the MAP can perform. However level 1 and 2 processing can ultimately be performed on the VOO as explained below.

The first level performs processing of raw data from a single sensor stream of a single domain. Such processing is usually very domain specific and does only include the knowledge of time relationship between data points. One can assume that no geometry information is available at this level, not even the relative offsets between sensors of the same domain.

The second level adds knowledge of the geometry allowing for algorithms with spatial dependencies to operate on multiple channels (same domain) of a single sensor system, e.g. all channels of the GPR array. At this second level it is even possible to fuse data streams from multiple domains and extract knowledge analyzing them jointly.

The third level can only be performed at the MAP, as it requires that data from multiple domains are available, properly geo-registered for joint processing or comparison. In addition the MAP will have access to data from multiple VOOs and data collected at the same location at different dates. This allows for the detection of changes to the roadway and bridge deck conditions over time using all available data.

Table 2: Processing Levels

Level	Description	Real-Time	Scope/Fusion
1	Sensor Subsystem Processing	Possible	Single domain, single sensor
2	Onboard Processing on VOO controller	Time-delayed	Multiple domains, multiple sensors, local geometry
3	Offboard Processing at Control Center	Post-processing	Multiple domains, multiple sensors, local and global geometry, multiple times

The processing solution has to built up over time as algorithms to analyze such data sets don't exist yet, because such data sets have not been acquired before the VOTERS project had completed its prototype. Once reliable processing algorithms have been developed additional processing options to the off-board post-processing on the MAP will become available. Level 1 processing as described above can then be implemented in hardware or software on the sensor subsystem for immediate processing as the data stream comes in. This has the potential of reducing the amount of data that needs to be uploaded to the MAP at the end of a day dramatically. In a similar way level 2 processing can be moved to the BOSS, as this VOO controller has access to the data from all sensor subsystems and the positioning system.

3.4.1 Streams

Each subsystem within VOTERS contains one or more sensors. The raw data of the sensor, as well as processed data from one or more sensors may be recorded as bulk data. To distinguish between different formats and semantic meanings of different bulk data, we define *streams*. A *stream* is a set of data in the same format and same semantic meaning. Note that one sensor can produce multiple streams. One stream can be the raw unprocessed stream, such as video images of the road surface. Another stream may be processed from the raw stream and show an image of detected cracks. Again, although both stem from the same sensor they are considered separate streams.

In order to identify streams, stream types need to be defined. Each stream instance then can be associated with a stream type. This enables the MAP/GIS to identify how to handle or display the bulk data.

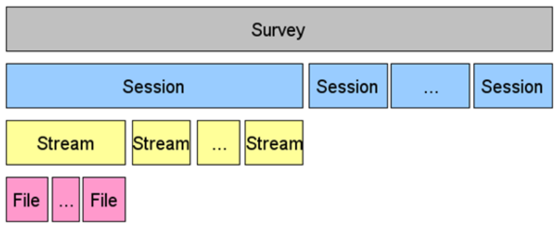

Figure 8: Bulk Data Hierarchy

The stream type does only define the type of data. More information is needed to identify how the stream is captured. A stream can consist of one or more files. An example of a stream file is a single image of a video stream. Each image of a video can be stored separately (e.g. as a jpeg image). Multiple image files make up a stream. Proper definition of the streams need to be complemented by definitions of the storage locations and automatically generated directory names, so that the upload of the bulk data can be triggered from the MAP and completed automatically. This requires several additional definitions (Fig. 8).

A *survey* defines a data collection run of the vehicle from the time it leaves the parking location to its return. A survey may consist of one or more sessions. A *session* defines the contiguous recording in the same configuration. Therefore, a survey may consist of one or more sessions. A new session is started each time the system configuration changes, or after a brief stop of the recording (e.g. when passing over an area of non-interest or parking temporarily). Each subsystem is responsible to record its own data. The base directory of data storage is defined throughout the VOTERS system and each subsystem has to conform with these standard configuration to achieve maximum automation. The stream files will be located in a directory that follows the naming convention below: $/var/voters/ < VooNr > / < Survey > / < SessionNr > / < SubSystem > / < Sensor > / < Stream >_{<} StreamQual >$.

Following a common guideline of storage location not only allows automation of bulk data upload, it also simplifies debugging and in field analysis as all systems will store data in the same manner.

3.4.2 Plugins

For displaying of streams, for processing of the raw data inside the streams, and for processing of processed streams plugins need to be defined. Plugins will be designed to process from one stream type (e.g. unprocessed data) to another stream type (e.g. feature extracted data) while being executable at all processing levels as long as the input stream matches. The generic processing of streams through plugins is depicted in Fig. 9.

Figure 9: Plugin Processing Streams

It is desirable to have the plugins developed in a way that they are able to run on-board, off-board and through the web-based interface to the MAP. This leads to the concept of a flexible plugin, which operates on a well-defined data stream and outputs another well-defined processed data stream. This allows to first develop plugin algorithms using recorded data at Level 3 executing on the MAP (FleetManager). With maturing of the algorithm, and given the requirement, the plugin can be moved to Level 2 or 1 for processing on the BOSS or even the sensor subsystems. To allow sensor fusion, a plugin can naturally operate on multiple data streams. An example is illustrated in Fig. 10.

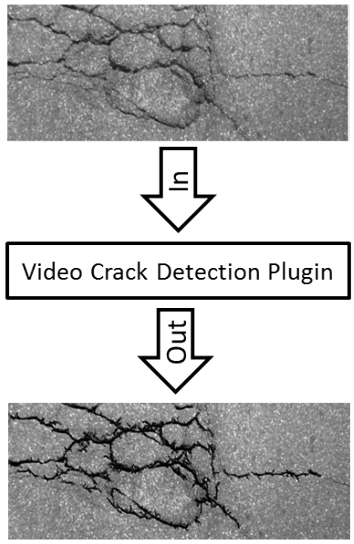

Figure 10: Example Crack Detection Plugin operating on Black and White video image input stream and creating binary image data stream of detected cracks and a text file containing statistics on the detected crack classes, e.g. 326673 total pixels, 1171 pixels or 0.36% transverse cracks, 76 pixels or 0.02% longitudinal cracks, 1201 pixels or 0.37% transverse cracks, and 2448 pixels or 0.75% diagonal cracks [14].

4. CURRENT STATUS

At the time of writing, we have established a centralized fleet manager running a MAP interface. We have equipped one VOO with positioning, acoustical, millimeter wave radar, and optical sensors. A GPR system will be added this summer. The communication scheme outlined above has been tested and timing synchronization within the VOO has been established. The VOO has already collected hours of data and we're approaching the first TB of raw data in our database.

5. CONCLUSION AND FUTURE OUTLOOK

The United States' infrastructure scores only a *D* in the latest ASCE report card [10]. The estimated $2.2 Trilion over 5 years investments needed to bring the condition of the nation's infrastructure up to a good condition indicate the severity of the situation. This paper has introduced the VOTERS project, which aims to assist in assessing the health status of the US road infrastructure. Through utilizing advanced sensor techniques, deployed onto VOOs, which are roaming traffic-embedded, a continues network wide road surface monitoring becomes feasible. This paper has outlined the basic collection framework and introduced major integration challenges and approaches. Initial demonstrations using a single VOO have been extremely promising showing the tremendous value of the data collected.

In the near future, we will finalize the automatic bulk data upload to ease collection of data, as well as realize the plugin structure. In parallel to the integration efforts, the VOTERS team actively invests into the development of additional sensors, e.g. for the outlined GPR sensors.

With the outlined scalable architecture, we are looking forward to a rapid extension of our road surface database. We will build up our repository data with the collected data runs. We are looking forward to additional researchers that assist in the evaluation of the recorded data and develop new data processing plugins.

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