Development of a USV-Based Bridge Inspection System

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***Abstract*— This survey explores: the requirements of and current techniques utilized in on-water bridge inspection; USV design and configuration considerations for USV-based bridge inspection; use of acoustic sensing techniques for imaging underwater bridge structures and channel bottom features; the control and dynamic positioning of USVs for bridge inspection; and lastly, the use of advanced robotics techniques, such as system localization and mapping for improving vehicle navigation under bridges and better mapping of bridge features.**

***Keywords*— unmanned surface vehicles, bridge inspection, robotics, autonomous systems, sonar imaging, human-robot interaction**

I. Introduction & Background

In the US, there are approximately 575,000 highway bridges and about 85% of them span waterways [1]. Nearly 25% of all bridges in the U.S. are considered deficient or obsolete and are in need of replacement. The task of inspecting and maintaining the nation's extensive network of bridges is arduous. Each bridge must be inspected at least once every two years, and more often when necessitated by age or structural concern. Thus, technological solutions that can make help make the bridge inspection process less costly, more efficient and safer for personnel are paramount.

Underwater bridge deficiencies and deterioration can have several causes, such as age, environmental degradation, excessing loading, collision damage, construction defects, poor design and shifting of the sediment that supports the substructures (scour, undermining). The inspection of bridge pilings at the waterline and underwater can be difficult. Fast flowing tidal currents, waves, strong coastal winds, and the presence of wildlife are common environmental factors that can make water-based bridge inspection hard and sometimes dangerous for personnel. Visual and tactile examination by divers is the primary method used for underwater bridge inspection. Tactile exams become necessary when the water is turbid and human inspectors must touch or feel bridge structures to detect flaws, damage or deterioration – it can be challenging to quantify the results of this technique [1], [2].

Given that so many bridges span rivers, canals, and saltwater areas, unmanned marine vehicles are an attractive technology for bridge inspection. There are several classes of unmanned marine vehicles, including: 1) remotely operated vehicles (ROVs), which are continuously teleoperated from a support vessel or shore base, 2) autonomous/unmanned underwater vehicles (AUVs/UUVs), which are preprogrammed to perform specific trajectories and then released to perform them without human intervention, and 3) unmanned surface vehicles (USVs), which are effectively robotic boats that can either be teleoperated or operated autonomously without human input. Trade studies of unmanned marine vehicles suggest that USVs are the most suitable for performing the entire scope of tasks required for robotic bridge inspection [3], [4]. USVs have been increasingly used in a variety of marine applications including ocean sampling, maritime search and rescue, hydrologic surveys, harbor surveillance and defense [5], [6], [7], [8], [9], [10].

Manned bridge inspection is a mature field that utilizes techniques developed over generations. Human-USV teams may one day be capable of performing semi-autonomous bridge inspection with initial surveys conducted by a USV to identify possible areas of concern, with more careful, targeted surveys handled by either follow-on USV-based measurements, diver-conducted inspections or, more likely, a combination of both.

This literature survey explores existing techniques and instrumentation currently used in manned underwater bridge inspection and how USV systems may be configured for use in autonomous bridge inspection. The remainder of this report is organized as follows: In Section II the requirements, goals and techniques of underwater bridges inspection are described in detail. Section III examines USV design and configuration considerations for USV-based bridge inspection, as well as acoustic imaging systems. A notional concept of operations for USV-based autonomous bridge inspection is also articulated. Lastly, the main findings of this study are summarized in Section IV.

II. Current Bridge Inspection Strategies

The primary goals of bridge inspection are to protect the safety and welfare of the public and to safeguard public infrastructure. Bridge inspections target both critical bridge deficiencies that could endanger public safety and non-critical deficiencies. As quoted from [11], [12] and [13], the main purposes of bridge inspections are to:

1. Provide for immediate action to limit the use of or close any structure which is revealed by inspection to endanger public safety.
2. Establish a chronological record of periodic and special inspections, listing structure components, component condition at the time of each inspection, thus allowing detection of progressive changes.
3. Determine the extent of any deficiency, critical or minor, resulting from deterioration or any other cause.
4. Enable bridge maintenance, repair, and rehabilitation to be programmed more effectively through early detection of structure deficiencies by which the public investment in the highway system will be safeguarded and repair costs minimized.

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5. Collect data on frequently occurring deficiencies to support a change in design and/or construction practices to eliminate the cause of the deficiency.
6. To collect, record and store bridge inventory and inspection data required to support the bridge management system.

A. Manned Bridge Inspection

Bridge inspection techniques are generally categorized along three broad lines:

1. Visual Inspection.
2. Non-Destructive Testing (NDT).
3. Material Sampling (Coring, removal and testing).

Typically, visual inspections are conducted first. Debris is removed to permit visual observation and measurement. Photography and video are used to record significant details. NDT is usually reserved for the augmentation of visual inspections in situations where additional, targeted measurements are required because an item of concern is discovered. NDT is generally not practical for large scale use on a bridge. Lastly, in cases where it is necessary to evaluate a structure before a major restoration, to search for hidden defects or to perform an analysis of the material properties of a structure, destructive testing is performed. As destructive testing typically requires that structural materials from various bridge components are sampled through coring or cutting, it is only done when necessary.

Both above- and under-water inspections must normally be conducted at least once every 24 months, but may be required more often after an unusual event (e.g. hurricanes, floods, earthquakes, fires, explosions and accidents), or when bridge components receive poor ratings in prior inspections. Moveable mechanical, hydraulic and electrical bridge components (including submarine cables) must be inspected at least once every 12 months. When the depth of water is less than 3 feet, underwater inspections are not required.

B. Underwater Inspection Techniques

Underwater inspection teams consist of a Lead Underwater Inspector, one or more additional divers, a tender (who is responsible for maintaining the dive station), and a boat operator. The size of an underwater inspection team varies, depending on the visibility of the water, the depth and whether or not air is supplied from the surface. In all cases at least one or two standby divers are required in case of emergency. When diving in enclosed or confined inspection areas, which are not large enough to accommodate two underwater inspectors, at least on inspector must be stationed at the underwater point of entry and an orientation dive line used.

The FHWA Underwater Inspection of Bridges (FHWA-DP-80-1) defines three levels of underwater inspection. The minimum level for an underwater bridge inspection is 100% Level I and 10% Level II.

A Level I Underwater Inspection is a swim-by inspection at arms-length of all underwater elements of the structure. When visibility is limited, the inspection consists of feeling all underwater structural surfaces. A Level I underwater inspection also includes looking for evidence of scour, the undermining of foundations and the exposure of normally buried portions of the structure.

A Level II Underwater Inspection involves cleaning and close inspection of a limited portion of bridge structures.

A Level III inspection is a highly detailed inspection of a critical structure or structural element, or a member where extensive repair or possible replacement is contemplated. This level of inspection involves extensive cleaning, detailed measurements, and selected non-destructive and partially destructive testing techniques.

1) Underwater Bridge Inspection Equipment

The underwater inspection process can be painstaking, as hand tools are used for either cleaning or measuring. For measuring, an underwater inspector may use a ruler, tape, calipers or levels. As with above portions of a bridge, visual inspection of underwater structures require that dirt, debris and organic growth (e.g. algae, oysters and mussels) are removed. The extent of the cleaning required depends on the amount of growth encountered and the type of inspection performed. For cleaning, underwater inspectors often use a chipping hammer, a scraper, a wire brush or a small pry bar. To speed up the inspection process, specialized underwater power tools are sometimes used for cleaning, drilling and cutting. The results of underwater inspections are typically documented using underwater paper and pens, notes recorded by a top-side monitor through voice communications with divers, voice recordings, and underwater cameras/videorecorders.

2) Bridge Components Surveyed in Underwater Inspections

Bridge features typically examined during underwater inspections include: piles; dolphins and fenders; piers and abutments; submarine cables; culverts and the channel bottom. Special attention is focused on examining steel structures for corrosion, concrete structures for cracks and wooden structures for marine borer attacks. The foundations around piers, abutments and culverts are examined for scour, erosion and undermining. Channel bottoms are also checked for scour and stream shifting.

III. USV Design and Configuration for USV-based Bridge Inspection

As noted in [4], surface vehicles are well-suited for unmanned, autonomous bridge inspection as they have important advantages over underwater vehicles: they can be more accurately controlled and localized through GPS, they can carry a larger payload, and they can continuously broadcast imagery data to observers in real-time.

A. Concept of Operations

It is anticipated that one of the main uses of USV-based bridge inspection systems will be for performing an initial survey of the underwater structure, the surrounding river bottom or seafloor, and the structure at and slightly above the waterline. The survey will be used to help inspectors identify areas of concern that a dive team should focus on and to understand when more targeted inspection, NDT and destructive testing techniques might need to be later applied. Current underwater bridge inspection teams consist of about 3-5 people. The USV-based bridge inspection system will be deployed at bridge sites by a team of comparable size. Possibly, dive teams that currently perform underwater survey could be trained to also use a USV-based bridge inspection system or supplemented with one or two more people, who specialize in the use of the USV-based system. The system will be deployed at remote or difficult to access sites from a light truck (e.g. pickup or van) and tended on the water by a small vessel, such as a john boat. It will be possible to launch the system from a small boat ramp, when available, or for it to be disassembled and carried to the water on foot. As part of its normal pre-inspection routine, the inspection team would use its knowledge of the bridge site and the results of prior inspections to select specific positions and corresponding bridge features that the USV-based system will be preprogrammed to survey. During the survey, the system will autonomously transit to the inspection site and then travel through desired waypoints while performing its measurements. It is likely that some measurements may require the vehicle to maintain a fixed position and orientation, thus the vehicle will have the capability of 'station-keeping' for several minutes at a time. For both safety and efficiency reasons, the system will have sufficient automatic obstacle avoidance and reactive trajectory planning capabilities so that it does not need to be continuously monitored by the inspection team. At the same time, the system maintains constant communications with the inspection team and relevant data are displayed in an easy to interpret user interface, so that its progress can be monitored and it can be temporarily teleoperated or redirected to an area of interest by the inspectors, whenever necessary. Telemetered data are recorded at the inspector's base station. Additionally, the sensor measurements, photos and video are recorded on board the USV to be downloaded later for more detailed post-processing and reporting. When a survey is complete or terminated by the inspection team, the USV can autonomously return to the launch point at shore. It would then be retrieved from either a boat ramp or on foot (after disassembly) and reloaded onto its light truck for transport.

B. Functional Considerations for System Design

The design of any system is driven by a combination of (often competing) requirements that ultimately determine its final configuration. The design requirements for unmanned vehicle based bridge inspection systems can be formulated taking into account the following basic considerations, among others:

1. Environmental Conditions:

a. USV-based bridge inspection systems will be deployed in tidal waters and rivers where currents can be strong. For example, it is common for tidal currents to approach 4-5 knots under bridges in the U.S. Intracoastal Waterway near Port Everglades in Dania Beach, FL. Unmanned inspection vehicles will need sufficient thrust to maneuver, and possibly hold position, in strong currents for the duration of an inspection mission.

b. The river waters flowing from inland to offshore often carry an abundance of vegetation, which can produce tannins that can reduce underwater visibility by giving the water a dark brown/tea color. Fast flowing waters can also transport a significant amount of silt, debris, and other organic matter, which reduces visibility. Thus, unmanned inspection systems will need the capability to operate in waters where visibility may only be a few inches (as low as 2-3 inches).

c. Marine growth often vigorously attaches itself to underwater structures. Technologies that permit the visualization of bridge structures through at least some common forms of marine growth, such as algae, are beneficial.

d. Unmanned marine systems performing underwater inspection may also be affected by waves when operating in coastal waters, or by the wakes of fast moving vessels when used in areas with substantial boat traffic.

e. Bridges located in coastal or open areas often experience a 'wind-tunnel' effect where air speeds up as it passes underneath and around the bridge structure. Strong winds can affect an unmanned vehicle's ability to accurately maneuver along a desired trajectory or to station keep.

f. Debris can sometimes collect at the base of bridge supports, especially after flooding. The USV should have a design (low draft, ducted propellers, etc.) and navigation system that reduces the likelihood of snagging on underwater obstacles.

g. The system should be capable of operating in water depths of 3'-25'.

2. Sensing Considerations:

a. It is expected that acoustic imaging technologies would be the most appropriate for visualization. The size, weight and powering requirements of these systems must be accommodated.

b. Additionally, an unmanned vehicle used for bridge inspection must have the capability of accurately knowing its position and orientation, so it is precisely understood to which parts of a bridge's structure a measurement corresponds. The large amount of metal in bridge structures can adversely affect sensors, such as flux gate compasses, so that heading information is not accurately known. One other possible issue is that positioning sensors, such as GPS systems, can require line of sight with overhead satellites. When passing under or near large bridges, the reception of GPS signals can be adversely affected [14]. Use of an acoustic imaging sensor across a long distance (6-30 feet) may require measurements to be motion compensated or the platform to be dynamically positioned (station keeping). This may involve the mounting of additional instrumentation, such as a precise inertial measurement unit (IMU), very close to the sensor itself.

3. Deployment Considerations:

a. Current underwater inspection teams consist of only 3-5 people. It would be desirable if the same team could operate an unmanned system during the course of their work, or if the system were deployable by a separate team of comparable size.

b. Given that some bridges are remotely located or difficult to access (owing to vegetation, traffic, etc.), it would be desirable for the system to be small enough and light enough to be deployed from a small truck and tended on the water by a small vessel.

c. The system should be sufficiently autonomous so that it does not need to be continuously monitored by the inspection team. It should also permit teleoperation or user redirection to areas of interest. After any interruption, the system should be capable of autonomously resuming its normal operation.

d. The system should have the capability of constant communications with the inspection team. When communications drop out, the system should automatically reconnect as soon as conditions permit.

e. The system should have a user interface that allows an operator to view measurements in near real time, in bright sunlight and in normal outdoor working conditions. The user interface should be capable of providing sufficient information and a balanced operator workload, so that bridge inspectors can make clear, well-informed decisions about the results of a survey in real-time.

f. During on-water travel to a bridge inspection site the vehicle may need to operate in the vicinity of other boat traffic. In such a circumstance, the ability of the system to autonomously interact with other vessels according to conventional navigation rules (COLREGs) could be very useful [15]. In addition, it may be necessary for the unmanned system to be capable of obstacle avoidance, to avoid collisions with stationary obstacles, such as bridge supports or underwater debris.

C. Hullform Design Considerations

From a design standpoint, one of the main advantages USVs have over manned vessels is that their configuration does not need to accommodate the space and safety requirements of human operators. Because of this, USV design can be more highly optimized according to sensing, maneuvering or deployment requirements. Thus, USVs come in a wide variety of hull forms [16], [6], [17], from Small-Waterplane Area Twin Hull (SWATH) vessels [10], [18] to tug boats [19].

USV design is sometimes almost entirely driven by sensing or automation considerations. Unfortunately, a very important, but often overlooked, component of USV design is hullform selection. The shape of the USV's hull has a tremendous impact on how much power is required to drive it through the water, which, in turn, affects the amount of time the system can be operated. The hullform also has an impact on the USV's seakeeping ability (response to waves), maneuverability (turning and straight line tracking motion) and overall suitability as a sensor platform. Often hulls are selected based solely on cost or availability, when substantial performance improvements can be obtained through a more careful consideration of the hullform.

A non-dimensional parameter called the Froude number F is typically used to determine the most appropriate hullform for a vessel and is defined as $F = U/\sqrt{gL}$, where U is the desired operating speed, g is gravity and L is the length of the hull. Thus, a combination of vessel speed and hull length determine the operating Froude number of a USV. Hullforms are categorized along three broad lines according to Froude number [20]:

1. $F < 0.4$ Displacement hulls: These tend to be very rounded. During operation, most of the weight of a displacement vessel is supported by the amount of water displaced. When operated at $F \geq 0.4$ the water resistance becomes very large and a substantial amount of power is required for propulsion.
2. $0.4 < F < 1.0$ Semidisplacement Hulls: This type of hullform is long and slender with a fine (sharp) bow, long straight midsection and blunt stern.
3. $F \geq 1.0$ Planing Hulls: Planing hulls are relatively short and blunt with a series of sharp corners called chines. Because of flow separation at the chines, planing hulls are typically inefficient at low speeds.

If it is assumed that a bridge inspection system may need to be operated in currents as high as 4-5 knots, then in order for the vehicle to make way against the current, it is desirable that it be capable of moving with a speed as high as 8 knots relative to the water. If the USV must be small enough to be transported by light truck and handled by a small team, then hulls no longer than about 14 feet would be desired. Based on this combination of vessel speed and length, the maximum operational Froude number of the USV will be about $F_{max} \approx 0.7$. Given that the vessel may be operated at values this large, it would be undesirable to use a displacement hull. As planing hullforms have more drag at low Froude numbers, a planing hull is not appropriate. The hullform most compatible with use in USV based bridge inspection is the semidisplacement hull. The most common types of semi-displacement hullforms include monohull (single hulled) vessels, catamarans (double hulled), trimarans (triple hulls) and SWATH vessels. Given that a USV-based bridge inspection system will need to be based on a fairly stable platform, with minimal wave- or current-induced motion, catamaran, trimaran and SWATH hullforms are preferable to monohulls. Trimarans tend to be stable, but are heavier, susceptible to wetdeck slamming in waves, and can be difficult to maneuver. Thus, SWATH vessels and catamarans are generally good choices for USV bridge inspection systems.

1) SWATH Vessels

As shown in previous studies [10], [18], SWATH vessels have good seakeeping properties and can provide nice stable platforms for bathymetric survey and sensing. An added benefit is that their large underwater hullforms typically have a long straight keel, which can be convenient for mounting wheels or treads, so that the vehicle can be operated amphibiously [18]. This feature can make deployment easier in hard to reach locations. A disadvantage of SWATH vessels is that they tend to have a large draft, which can increase drag and make passage in areas with underwater debris difficult.

2) Catamaran Hullforms

Catamarans may be the best all-around choice of hullform to use for the range of conditions expected during USV-based bridge inspection. They have: low drag characteristics over the range of operational Froude numbers expected; can provide a stable sensor platform, which can be further augmented through the use of advanced suspension techniques to provide good seakeeping characteristics [21], [22]; and they can be easily configured with dual propellers at each transom stern to use differential thrust for maneuvering, which simplifies control and improves maneuverability.

D. Propulsion System Design Considerations

In principle, both waterjet and propeller based propulsion are well-suited for bridge inspection USVs. An advantage of using waterjets is that they can be configured to be operated near the maximum efficiency of a DC motor without the need for gearing [23]. Waterjet systems also have a lower draft than propellers as their inlets can be configured to be flush with the bottom of the hull, whereas propellers must be submerged at least one propeller diameter beneath the waterline to prevent ventilation. However, small, low speed waterjets are not common place. Thus, smaller waterjet propelled USV designs tend to utilize RC hobby systems, which suffer from low mechanical reliability and can be easily damaged by the intrusion of waterborne debris. Waterjets designed for jetskis are more robust, but are intended for higher operational speeds (~55 knots max.) and so are not well-suited to the much lower speeds (~8 knots max.) expected to be appropriate for bridge inspections.

Some propeller systems, such as electric trolling motors [18], [24], [25], are a good choice as they are mass produced for the recreational fishing industry, relatively inexpensive ($USD 200-300), widely available, and are designed to be operated over the range of speeds required for USV-based bridge inspection. One drawback of trolling motors is that they should be augmented with an add-on duct or fairing as they are generally produced without one and can be a danger when operated near divers. An additional option would be to purchase ducted propellers designed for underwater ROVs. While these are usually fairly rugged and provide a substantial amount of thrust, they tend to be expensive.

E. Powering Considerations

A power-related systems engineering issue of importance for transport is the type of battery storage to be used on-board the USV. LiPo batteries are lightweight and well-suited for unmanned systems, but are considered hazardous materials and can be difficult and costly to ship. Some manufacturers are now regularly shipping large LiPO battery packs with their small boat propulsion systems. These appear to be fairly robust, but are currently more costly than other alternatives, such as AGM Lead Acid batteries. Deep cycle marine AGM Lead Acid batteries are inexpensive and can be purchased at almost any auto parts store. However, their high weight reduces the amount of instrumentation/payload that can be carried aboard the USV and makes deployment more cumbersome. Possible powering configurations to consider for the future development include the use of hybrid fossil-fuel/electric power [26] and the use of fuel cells [27], [28].

F. USV Imaging, Autonomy & Control Considerations

Today, unmanned surface vehicles (USVs) are not truly capable of 'persistent autonomy' due to the wide variety of tasks they must perform and the complexity of their operating environments. It is likely that early versions of a USV-based bridge inspection system will rely on relatively simple autonomous systems that use scripted operations and waypoint tracking to perform surveys. However, in the long run there are several developing methods in robotic planning and decision making that should be applied to make the operation of such systems robust, reliable and easy for bridge inspectors to use.

Murphy et al. [4] performed a preliminary study of bridge inspection using USVs, AUVs and ROVs, in the context of hurricane recovery. The USV was able to transit to the inspection site autonomously, but the survey itself was conducted using teleoperation with one person responsible for controlling a DIDSON imaging sonar and a second person responsible for positioning the vehicle. The team noted several challenges with bridge inspection, most importantly having to do with localization, station-keeping and determining the relative alignment between the imaging sonar and vehicle. The work identified several milestones for the improvement of post-disaster bridge inspections, which are also applicable for routine bridge inspections. They are paraphrased here:

1. *Standardize mission payloads.* UMVs should have an acoustic camera and a video camera to cover both high and low levels of turbidity. Given that inspection may involve slow movements close to structures, side scan sonars which rely on motion do not appear appropriate.
2. *Health monitoring.* A UMV should have sufficient sensors or encoders to correctly determine the position of its components and its overall health.
3. *Improved teleoperation through better human-robot interaction*. HRI is a significant weakness in UMVs. Studies are needed to resolve competing displays, while payloads such as two-way audio and extra displays can facilitate team coordination.
4. *3D obstacle avoidance.* UMVs need to avoid obstacles above and below the waterline but also consider the tides and depths. Obstacle avoidance is expected to speed navigation and improve the overall safety of operations.
5. *Station-keeping.* Significant advances in vehicle control must be made to enable station-keeping. This is expected to reduce the load on the mission specialist and engineers because they have a steady image to look at and eventually reduce the number of people involved in the robot team.
6. *Handle large data sets.* As UMVs become more successful at inspection, a huge amount of imagery and data will be generated and must be handled.
7. *Cooperative sensing.* Current systems put the responsibility for surveying the entire structure and identifying damage or scour on the human. Advances in control and in image processing should be able to ensure coverage of the structure and assist the image interpretation by cueing areas of interest. These advances in control theory and artificial intelligence would likely increase performance and the reliability of the inspections.

Here, some of these topics and some additional considerations are discussed and expanded upon.

1) Mission payloads – Imaging technologies

Underwater imaging techniques can utilize both optical and non-optical technologies [29]. Optical approaches include underwater photography and underwater videography. Non-optical techniques include sonar (acoustic), laser and radar systems.

The image quality of optical systems is strongly affected by turbidity. Additionally, the camera range and lighting of photographic systems often prohibit a panoramic view, so that only two dimensional perspectives are possible. Thus, non-optical technologies perform better for underwater bridge inspection [30].

Laser techniques, such as scanning LiDAR, can produce accurate underwater images, but possess limited range in turbid water [31], [32]. It is more widely used in the inspection of offshore structures were water clarity is less of an issue. Current research has focused on combining LiDAR with photographic and acoustic techniques to produce high quality images.

Radar technologies can produce underwater images of internal defects, such as cracks in concrete structures or subsurface channel-bottom geotechnical strata layers, and Synthetic Aperture Radar (SAR) can be used to image large areas of seafloor topography [30].

Of all of the approaches, acoustic (sonar) imaging techniques appear to have the most promise for underwater bridge inspection, as they can be used in very turbid waters. Sonar imaging techniques can be broadly classified as either 3D or 2D techniques. 2D systems tend to have the best definition when the angle of incidence is very high and 3D systems work better when the angle of incidence is low [30]. Sonar imaging techniques appear to be most promising for: the rapid assessment of a bridge's underwater structure; scour detection and documentation; underwater construction inspection; and enhancing diver safety and efficiency at challenging dive sites.

2) Improved teleoperation via better human robot interaction

Sparse advisory control refers to the ability to have a robotic system, such as a USV, mainly perform its work autonomously (independently of a human operator), with occasional inputs from a person in either the form of updated mission directives to be performed autonomously or complete teleoperation (manual remote control). A goal of sparse advisory control is to create a seamless transition between autonomous operation and teleoperation along a continuously sliding scale. The implementation of sparse advisory control requires the successful integration of three main components: (1) the software architecture of the autonomous agents; (2) a means of implementing 'sliding autonomy'; and (3) a human-robot interface that provides sufficient situational awareness, while still permitting a user to rapidly switch between tasks. The software architecture must facilitate the computational speed required for the calculations involved in integrated decision making, task assignment and trajectory planning, especially in systems where regular communication interruptions can occur. Since human operators are not guaranteed to be monitoring the USV at a given time, deciding when a USV should seek assistance from a human operator on an assigned task is an important question. Associated with this are a number of important research issues:

- What is the minimum number of human operators in the team needed?
- How can sufficient situational awareness be provided to human operators so that they can focus on their main tasks, but still be able to guide the progress of the USV?
- Under what conditions should a human operator teleoperate a USV?

Prior research along these lines has involved the exploration of 'common agent architectures, such as logic-based agents, reactive agents [33], behavioral agents [34]; belief-desire-intention (BDI) agents [35], and layered architectures. For unmanned vehicles, it has been found that the more tractable architectures are those based on the use of layers of abstraction, where decision making, sensing and actuation are separated so that the number of internal states of a system can be kept to a minimum [36], [37]. The architecture of individual agents within robot teams tends to have three or four layers [38], [39].

Mixed-initiative interactions between robots and human operators can be used in their collaborations [38]. The interactions consist of either the human or autonomous system deciding upon who is in control of aspects of a given task. The goal of the decision-making process is to optimize metrics, such as the expected time to complete the task or overall mission goal and the robustness of the process. Execution of a task may switch between human or robot control based on past performance, such as number of failed attempts or duration.

An important component for the implementation of multi-agent sliding autonomy is the design of the human interface. How quickly a human operator can re-attain situational awareness when transitioning between tasks is crucial for the overall performance of a human-robot team. Important questions are how much information should be presented to the human user, how should it be presented and how much data should be buffered or saved. UAV studies of human performance have suggested that humans are inherently bad at planning when presented with many complex possibilities and with an increased workload. They also suggest that more guidance on task scheduling should be provided as part of a user interface [40]. It may be possible to develop adaptive scheduling algorithms that monitor a human user's performance over time and adjust the scheduling algorithm and team to improve the team's overall performance.

3) 3D obstacle avoidance and trajectory planning

It is not possible for a software programmer to anticipate the infinite number of possible situations a USV might encounter in the field. In order for USVs to operate in complex environments, such as near bridges and in ports, a combination of advanced deliberative and reactive task and trajectory planning is necessary. This may be achieved through a realized set of "automatically-generated" behaviors, which enhance the planner so that it considers different classes of situations in pre-programmed ways, while taking the inherent limitations of the vehicle's dynamic response into account [15].

Efficient and safe navigation in cluttered, dynamic environments requires the prediction of the future movement of dynamic obstacles that can interact with each other in complex ways. A suitable trajectory planner needs to reason about the risk associated with an avoidance maneuver and the availability of contingency maneuvers to counteract unexpected scenarios as they arise. Recent work in this area includes the development of a model-predictive trajectory planning algorithm for USVs operating in civilian traffic [41]. Here, the planner reasons about the availability of contingency maneuvers needed in case any of the civilian vessels breaches the COLREGs [42].

4) Station-keeping

The environments around bridges can be strongly affected by wind, tides and wave conditions. The resulting currents and swells can vary substantially, both in time, and in space as a USV maneuvers around a bridge structure. Thus, USV-based bridge inspection will require robust station-keeping capabilities. Among the most important tasks expected to require this are object localization, feature imaging and possibly the launch and recovery of smaller subsystems [25].

Station-keeping requires collaboration between the controller and the propulsion system, both designed to allow the vehicle to perform this challenging maneuver. Small external perturbations, such as wind, waves and current, can have tremendous effects on low weight USVs. These can negatively affect the USV's ability to hold its state, resulting in large errors or oscillations. A robust controller capable of accounting for unmodeled dynamics, which lead to significant deviations between simulated and experimental results, is therefore essential.

One basic issue with much of USV control law development is that it is often limited to numerical simulation or small-scale experiments, rather than full-scale sea trials [43]. In fact, even in more technologically mature fields, such as AUV control, stabilization in the presence of environmental disturbances has only been partially addressed [44]. Several solutions have been proposed for the station-keeping of surface vehicles. In [45], experiments were performed on a small underactuated USV with high windage, where a feedforward wind model was modified to accommodate a PD-based heading autopilot. Switching between point and orientation stabilization and discontinuous control was employed to stabilize a marine vehicle to a point in the presence of a current using dipolar vector fields as guidance in [46] and [47]. Similarly, a hybrid approach was taken in [48] where multi-output PID controllers with and without acceleration feedback were used to stabilize a vehicle in high sea states by the use of an observer to estimate the peak wave frequency. The controller switched to controllers better suited to handle large disturbances as the peak wave frequency estimate decreased and, correspondingly, the sea state increased. Aguiar and Pascoal [44] devised a nonlinear adaptive controller capable of station-keeping an AUV with uncertain hydrodynamic parameters in the presence of an unknown current. Backstepping also was suggested in [49] as means to station-keep a fully-actuated vehicle, although environmental disturbances were not explicitly stated in the problem formulation.

In [25], experiments of station-keeping controllers in environments of uncertain wind, current and wave disturbances show that the USV tested is best controlled by a nonlinear, backstepping, Multi-Input Multi- output (MIMO) PD controller, when coupled with a Lagrangian multiplier method for the control of thrust allocation. The USV was found to be capable of reaching and maintain a specific configuration of heading and position for a periods of ten or more minutes.

5) Wind Feedforward Control

As mentioned in Section III.B.1.e strong winds can exist around the base of bridges. In general, it has been found that wind can act as a strong disturbance on the station keeping operations of marine vehicles [50]. As USVs tend to be light weight and have a large windage areas, they are generally even more sensitive to wind disturbances than much larger vessels. Robust feedback controllers can be used to attenuate slowly changing wind disturbances, but have difficulty compensating for the rapid variation of wind speed and direction [51]. While there are a great number of studies concerning the automatic feedback control of USVs, feedforward control, such as wind feedforward control, still has not been widely explored. The main challenges encountered when designing wind feedforward controllers include:

1. Accurately measuring representative wind speed and direction. It has been found that wind gusts and turbulence can cause large measurement errors [50]. Anemometers should be mounted to ensure that measurements are minimally affected by wind interaction with the vehicle's structure.
2. Few wind models for estimating the wind forces and moments acting on small marine vessels have been developed. Most existing wind models were developed for large vessels, such as oil tankers, and commercial ships [50], [52].

In [24] control and sensing strategies were developed to mitigate wind effects on a 4.9 meter long, 180 kg USV. A wind feed-forward controller was designed using an anemometer to measure the apparent wind speed/direction and a wind model to estimate the wind-induced forces and moments on the USV in real-time. Freely drifting tests were performed to evaluate the impact of the wind on an unpowered USV. The wind was strong enough to blow the vehicle more than 20 meters off station in 5 minutes when the mean wind speed was about 2m/s and the vehicle was allowed to freely drift with no control. Wind feedforward was added to different station-keeping feedback controllers, namely a PD controller, a robust backstepping controller, and a sliding mode controller. Station keeping tests of those controllers without/with wind feedforward controller show that a small USV can gain significant benefits from the inclusion of wind feedforward feature in both position and heading by an average of 75%, and 46%, respectively. It is likely that similar control strategies can be developed to handle the effects of strong currents due to tides, provided that suitable sensors can be identified.

6) Positioning

A concern of USV-based bridge inspection is that operating in the vicinity of a large bridge structure can affect precise positioning as GPS line of sight to overhead satellites may be blocked by parts of the structure. Use of sensor Kalman-filter based sensor fusion techniques can be used to improve positioning through combining dead-reckoning and GPS measurements to produce an improved estimate of a vehicle's location and heading. An additional solution would be to use Real Time Kinematic (RTK) GPS positioning technology, which can precisely measure a vehicle's position with respect to one or more fixed base stations.

System Localization and Mapping (SLAM) is an automated map-building technique, which can be used to estimate the position of a robot within its environment [53], [54]. SLAM allows one to probabilistically build a map of its environment by combining estimates of its motion with sensor observations. SLAM has been implemented on a USV to combine LiDAR measurements, imagery from a spherical digital video camera, an inertial measurement unit (IMU) and a Doppler Velocimetry Logger (DVL) for vision based navigation and mapping under bridges [14]. Using GPS measurement updates, when available, to ground-truth position estimates it was found that SLAM-based navigation was better able to track vehicle position than traditional dead-reckoning and that a significant improvement in mapping of the bridge structures could be obtained. SLAM based navigation and map building are a form of 'cooperative sensing' technique, where data collected from different types of sensors and sometimes from different platforms (vehicles) are combined to produce an improved estimate of the state (position, orientation and speed) of a vehicle. An area of study that appears to be very promising would be to combine optical data taken using LiDAR and camera systems above the waterline with sonar imaging data of underwater structures and the channel bottom to build more accurate maps of a bridge's structure, which should also help to assess its condition through the identification of multiple features.

7) *Cooperative sensing/Multi-session Mapping*

Extracting maps from marine survey data can be time-consuming because it requires large amounts of manual de-noising and adjustment. The process can be improved using SLAM. Prior work in this area includes robotic mapping of the seafloor using USVs [55] and AUVs [56] robotic mapping on the ground [57] and from the air [58]. These approaches typically span small time scales, assuming that the mapped environment remains largely static during mapping. An interesting application of SLAM would be to capture changes in bridge structures using maps obtained over repeated bridge inspections.

Such multi-session mapping could be enhanced by incorporating informative path planning, which is a decision-making process that instructs the vehicle about where and how to intelligently gather more measurements. This type of planning can assist the mapping process by increasing the efficiency and increasing quality of the resulting maps. Recent work on informative path planning for environmental mapping includes research of active SLAM [59], [60], planning for information gathering [61], and uncertainty-aware planning for efficient area coverage [62], [63].

IV. SUMMARY

Manned inspection strategies, requirements and techniques of underwater bridge inspection have been explored. Use of a USV-based inspection system utilizing an imaging sonar may be most effective for: the rapid assessment of a bridge's underwater structure (e.g. detecting spalling, scaling and foundation undermining); scour detection and documentation; underwater construction inspection; and enhancing diver safety and efficiency at challenging dive sites. A concept of operations that envisions a small team of 3-5 people using a USV with sparse advisory control for bridge inspection is articulated, along with several considerations for the design and configuration of USVs developed for bridge inspection. It is suggested that hullform selection should be a serious consideration in USVs designed for bridge inspection and that semidisplacement hullforms would be most appropriate for most bridge inspection applications. It is recommended that non-optical imaging techniques, such as real-time, multi-beam sonar will work best for bridge inspection below the waterline. Owing to the need for operating in currents, wind and waves, inspection USVs should have dynamic positioning capabilities, such as station-keeping and wind/current feedforward control. In the long run, the performance of human-USV inspection teams will improve as emerging advanced robotics techniques continue to develop, especially in the following areas: human interface design; automatic behavior generation for task and trajectory planning; and system localization and mapping (SLAM) for multi-session mapping. An approach that seems to be particularly promising is SLAM that combines optical measurements (LiDAR and camera data) above the waterline with underwater sonar data for improved navigation under bridges and better mapping of bridge features.

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