Enabling over the horizon operation on a line-of-sight uncrewed surface vehicle

1st Michael P. Scherer
Chance Maritime Technologies
Lafayette, LA, USA
michael@chancemaritime.com

2nd T. Stuart Chance II
Chance Maritime Technologies
Lafayette, LA, USA
stuart@chancemaritime.com

***Abstract*—Uncrewed Surface Vehicles (USVs) augment existing maritime capabilities to increase the operational tempo for a mission, allowing more data to be collected in the same amount of time as a purely crewed mission. Many USVs operate within line-of-sight of the control station, utilizing point-to-point or mesh radios for communication. Although still beneficial for increasing data collection, this approach has the disadvantage that subject matter experts still must mobilize on-site with the craft, thus not leveraging the benefits of remote work. Enabling remote work increases access to opportunities in the blue economy. To leverage this paradigm shift, a USV which was originally intended to be used only within line-of-sight was converted to over-the-horizon capable with the implementation of three key modifications to communications, situational awareness, and local control. This paper presents the design, development, and operation of the USV for over-the-horizon operation.**

***Index Terms*—Autonomous vehicles, Telerobotics, Marine robots, Maritime Communications, Uncrewed surface vehicles, Unmanned surface vehicles**

I. Introduction

Line-of-sight Uncrewed Surface Vessels (USVs) have demonstrated increased operational throughput over purely crewed operations in the field of hydrographic survey [1]. Although these benefits are significant, they do not take advantage of modern remote work paradigms as crews must still be within radio range of the USV. Remote work paradigms have increased access for individuals who are unable to go to sea due to physical disability, cost, or lifestyle [2]. Line-of-sight USVs additionally require personnel on-site, and therefore require additional services and accommodations to support them. In particular for longer duration missions, on-site staff require desk space for control stations on board a mother ship, bunk space, food, water, and other services which drive operational costs [3]. Over-the-horizon operation of USVs reduces mobilization and operational costs as subject matter experts do not need to travel with the vessel. It also enables enhanced remote assistance capabilities even if the vessel is operated within line-of-sight, allowing the expertise of senior subject matter experts to be shared across multiple missions. This increases the capacity of organizations conducting marine science and improves supervisory support often missing for young researchers [4].

This paper discusses the conversion of an USV from only being operable within line-of-sight to being operable over-the-horizon. The USV used was an existing vessel in Chance Maritime Technologies' (CMT) lease pool that has a third party remote/autonomous control system. Satellite communication systems were added to operate the vessel over the horizon. Althought cellular 4G/5G operation could be considered over-the-horizon, coverage is not truly global, even in remote inland locations. Situational awareness was improved to ensure its adequacy for operating over the horizon, motivated by studies which have shown that lack of situational awareness is the dominant cause of maritime accidents [5]. The controller was also reconfigured for operation local to the vessel, and procedures were developed to ensure safe handoff between the remote and local operators.

II. Existing Platform

The *Inland Protector* is a mini tug USV that is a 3.48m [11ft 5in] long autonomous craft, originally built for line of sight operation, shown in Figure 1. Communication with the vessel was accomplished with redundant Silvus mesh radios on 5 GHz and 2.4 GHz bands. The vessel is powered with an 80 Hp direct drive diesel engine. It has a top speed of 6.8 knots, and an endurance of 19 hours at a cruising speed of 4 knots with a 20% fuel reserve.

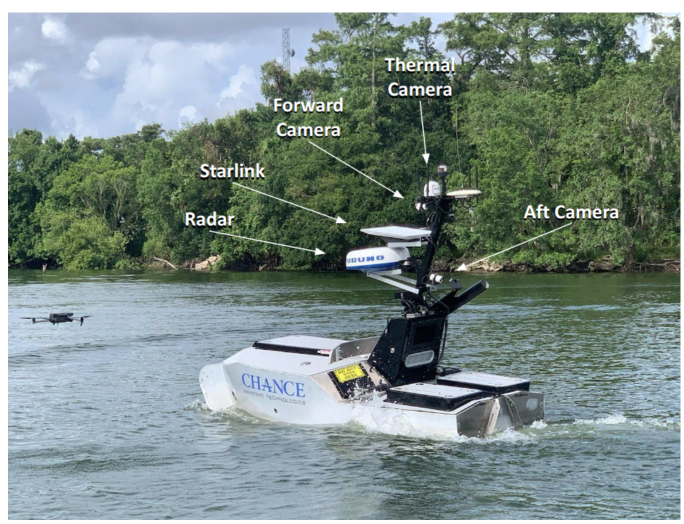

Fig. 1. Chance Maritime Technologies' *Inland Protector* USV

III. Modifications

The revised architecture of the USV is sumarized in Figure 2.

The base USV platform only possessed line-of-sight mesh radios. Starlink satellite communications were added to enable mission planning and remote operation from Chance Maritime Technologies' Operations Center in Lafayette, LA, USA.

For situational awareness, the base USV possessed forward and aft facing cameras, as well as a satellite compass for localization. Sightlines athwartships were not visible to the remote operator, and situational awareness was limited to what could be seen within the resolution of the visual cameras. Additionally, operators had limited ability to perceive depth/range of obstacles from monocular cameras which posed a safety risk [6]. In order to maintain an adequate lookout [7] with $360°$ visibility, a remotely operable radar system was added for increased situational awareness and ranging around the craft.

Finally, the hand controller was reconfigured to work directly with the boat to allow local launch & recovery operation while the vessel is monitored remotely. This proved necessary as low latency communications were found to be vital for fine-tuned maneuvering and coordination with local crews. Local control was further in place as an emergency fallback should the satellite communications system fail.

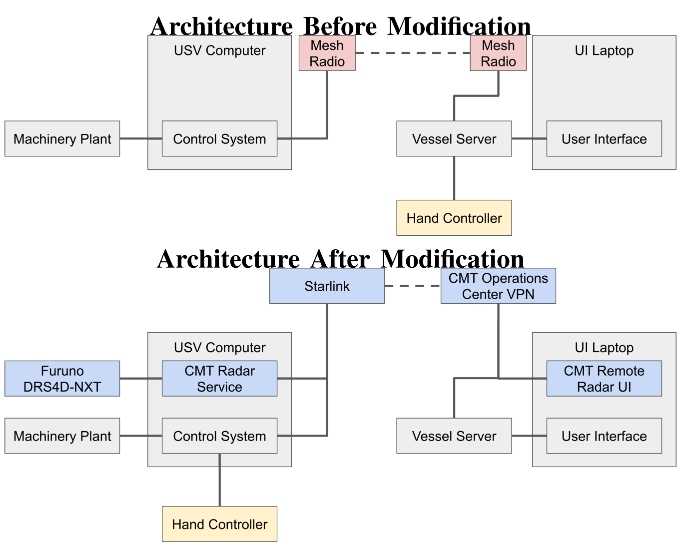

Fig. 2. Architecture before and after modifications; removals in red, additions in blue, and moves in yellow

A. Satellite Communications

Several over the horizon communication systems were considered for the *Inland Protector* USV, shown in Table I. Systems which required a dome or antenna footprint greater than $0.7m$ x $0.7m$ were not considered due to size constraints on the USV's mast. Starlink was chosen for its large data bandwidth, affordable price, and global coverage. Fixed antennas, such as those used by 4G, Starlink, and Iridium SBD are advantageous for marine applications where the vessel may roll frequently and would otherwise require constant gimballing. The bandwidth of Starlink is comparable to the bandwidth of 4G/5G cellular networks; however, the global coverage is a significant advantage, even in inshore locations where cellular coverage is unavailable. Iridium Short Burst Data [8] and Iridium Rudics [9] were not considered due to their extremely low bandwidth communication capabilities which were inadequate for this application.

The base package of Starlink does not provide a static IP for the USV. To give the vessel a well known address and to secure communications over the internet, the Starlink was plugged into a dedicated network port on the USV's control computer, and a VPN connection was established to the Chance Maritime Technologies Operations Center. There, IP addresses were reserved on the DHCP server for the USV Control Computer, Vessel Server, and UI Laptop. These well known IP addresses were then used to configure all comunication traffic between the USV and the Operations Center.

B. Situational Awareness

A Furuno DRS4DNXT marine radar was installed on the vessel to provide additional situational awareness. A Remote Radar system was developed to control and monitor the radar over the satellite link, consisting of a *Radar Service* application running on the vessel, and a *Remote Radar* user interface. The Radar Service interfaced with the radar using the Furuno API. Radar azimuths were encoded into Protocol Buffer (protobuf) [14] messages and then transmitted to the Remote Radar user interface with UDP. The Remote Radar interface decoded the azimuths and rendered them in a head-up display, shown in Figure 3. UDP was chosen over TCP because although the link is assumed to be lossy, fast delivery of the latest information on the vessel's state and surrounding obstacles is critical for safe operation.

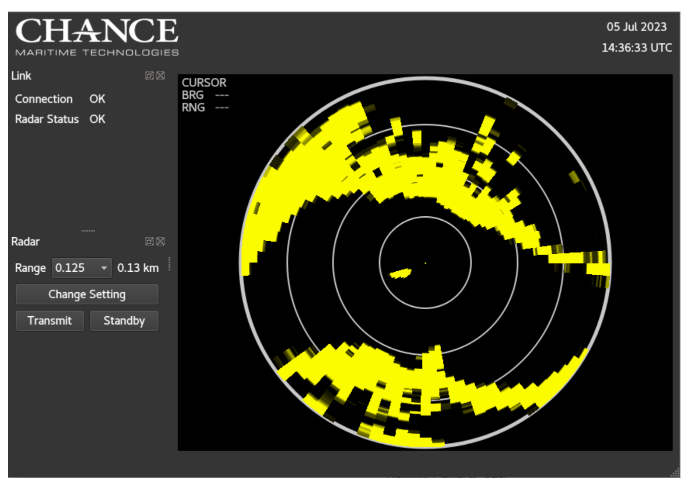

Fig. 3. Remote Radar User Interface

Without compression, the radar azimuths and associated metadata required 4,241 kbps of bandwidth. Compression of the azimuth data was accomplished using zlib [15]. Zlib compression was chosen for its run length encoding scheme which could efficiently deflate the high prevalence of empty regions

TABLE I
SATELLITE COMMUNICATION OPTIONS CONSIDERED

System	**Network**	***Bandwidth Up***	***Bandwidth Down***	***Nominal Power***
Starlink [10]	Starlink (Mobile)	10 Mbps	50 Mbps	150.0 W
Starlink [10]	Starlink (Priority)	25 Mbps	220 Mbps	150.0 W
VesselLINK 200 [11]	Iridium Certus	176 kbps	176 kbps	65.0 W
VesselLINK 700 [11]	Iridium Certus	352 kbps	704 kbps	65.0 W
Sailor 150 [12]	Inmarsat BGAN	150 kbps	150 kbps	120.0 W
Sailor 250 [13]	Inmarsat BGAN	284 kbps	284 kbps	150.0 W
Sailor 500 [13]	Inmarsat BGAN	432 kbps	432 kbps	150.0 W

in radar azimuths. This reduced bandwidth requirements by a factor of seven to 599 kbps.

Controls for changing the range, transmit, and standby modes were also added, which also utilized protobuf messages over UDP. Configuration parameters are encoded in a single *Configuration* message as optional fields. Heartbeats are exchanged by both the Remote Radar and the Radar Service applications, transmitted at 1Hz. Heartbeat messages indicate connectivity to the Remote Radar user interface such that the user can distinguish between a failure of the Radar Service application and a failure with the radar hardware itself. The Radar Service application uses the heartbeats from the Remote Radar user interface to automatically stop transmission when no user is connected after ten seconds. In addition to power savings, the automatic stop was added as a safety feature to mitigate the small risk of hazardous radiation exposure while the vessel is recovered from a radar left transmitting.

C. Local Control

To ease launch and recovery operations, and to allow for local intervention in case of emergency, the hand controller was reconfigured to interface directly with the USV over the vehicle's onboard WiFi. A network configuraiton was added to the hand controller to connect to the network addresses and ports of the vessel directly. A new RTSP media server was initialized on the boat to serve video data to the hand controller's display.

IV. COMMUNICATION AND HANDOFF PROCEDURES

Communication and handoff procedures were created to ensure the USV had a persistent watchstander between local and remote operating stations. The vessel utilized an existing mechanism whereby any operator can "take control" of the vessel at any time with a single button press. To alleviate confusion, a cellular voice link was maintained between local and remote operators. The operators indicated positively prior to taking control under normal operating conditions. Local operators were given liberty to takeover manual control if the vessel risked collision. Both local and remote operators had the ability to see who was in control at any time through the third party control system; however, verbal confirmation of control handovers still proved useful because there were no built-in alerts when control changed hands.

For operation, the local and remote operators performed a loop check on site where they verified that situational awareness sensors were functional, and that both the remote and local operators could take control of the USV, start its engines remotely, actuate the gear control, adjust throttle & rudder, as well as ESTOP. The local operators then launched the vessel from its trailer down the slipway into the trial lake. They utilized the hand controller to drive the USV off of the trailer and to a safe distance from the shore and dock. From there, after positive confirmation the vessel was safe for operation, as well as verbal confirmation by the remote operator to the local operator of the intended initial path of the vessel, the remote operator took control and initiated the autonomous mission. Multiple missions were tested to exercise remote mission planning and changeover.

After completion of missions, the remote operator sent the USV to a waypoint plotted within range of the slipway but well clear of the dock. The USV was set to drift upon reaching the waypoint. The local operators then took control of the vessel using the hand controller and drove it onto the trailer.

V. EXPERIMENTAL RESULTS

The traffic to and from the vessel was captured using `tcpdump` [16] to analyze traffic statistics shown in Table II. With a total of 1.5 Mbps of uplink required to operate the system, Starlink is the only communication system that has the capacity to operate this system over the horizon without further optimization, within the space, weight, and power capacity of the USV.

TABLE II
BANDWIDTH USAGE

System	**Uplink (kbps)**	**Downlink (kbps)**
Base Telemetry	111.42	3.06
Cameras	862.15	0.00
Radar	483.10	0.44
Total	1,456.66	3.51

For testing, a 5m [16.5ft] long zodiac was run in the lake around the vessel to asses the radar's ability to detect an obstacle, shown on both the radar and the thermal camera in Figure 4. Although the thermal camera was effective at providing a high contrast visualization of the contact, the relatively low resolution (640x480 pixels) and narrow field-of-view (25°x19°) reduced the ability of the operator to identify obstacles except when they were directly in front of the vessel.

During operation, the visual camera system on the third party control system occasionally showed old images inter-

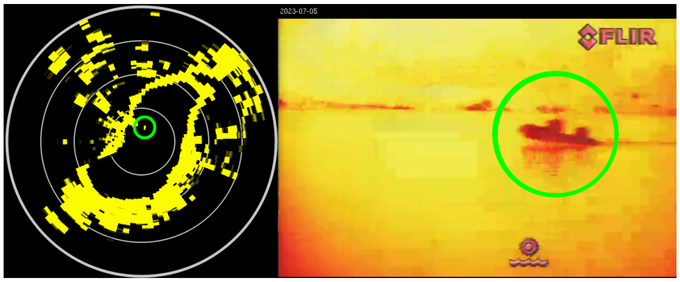

Fig. 4. 5m zodiac detected by radar and thermal camera

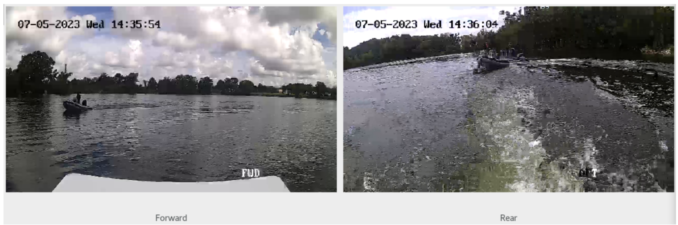

Fig. 5. Zodiac appears in both fore and aft cameras in third party control system

leaved intermittently, as shown in Figure 5. Packets were frequently transmitted out of order as discovered through analysis of the captured packet logs. On one camera stream, an average of 87 out-of-order RTP packets were transmitted per minute over the course of operation. Implementations can make use of a jitter buffer to reorder and ultimately drop out-of-sequence RTP packets [17]; however, the control system did not appear to implement such functionality. The high frequency of out-of-order packets may be attributable to Starlink's satellite switching, or its inter-satellite link (ISL) routing strategy [18]. The CMT Remote Radar system dropped out-of-order packets which prevented erroneous azimuths without adding latency. The erroneous imagery in the cameras reduced operational reliance on the camera system, increasing dependence on the radar to identify the contact.

VI. Conclusions & Future Work

The communication system using Starlink was shown to have more than sufficient bandwidth to support over-the-horizon operations. Situational awareness on the USV was improved significantly with the addition of the remote radar system, adding full 360° visibility as well as depth perception for remote operators. The operational concept of connecting the hand controller to the USV's WiFi was effective for launch and recovery operations, which would otherwise be more complicated to execute remotely.

The situational awareness system will be upgraded to leverage the Automatic Radar Plotting Aid (ARPA) functionality built into the Radar. ARPA contacts can then provide additional information to the operator including automated proximity alarms as well as alarms for Closest Point of Approach (CPA). Overlays with Automatic Identification System (AIS) plots would further improve the situational awareness of the operator. However, as this particular vessel is better suited for inland operation, AIS is less commonly used and therefore less critical for operations.

The Situational Awareness can further be improved by replacing the baseline third party camera solution with a new system robust to out-of-order package transmission.

Compression of radar data could be further improved to reduce the volume of data transmitted. One form of compression would be to quantize the data and pack between two and four bits per pixel rather than the current eight bits per pixel.

A sponson will be added for additional space and fuel to support scientific payloads. This will extend the endurance of the craft which will enable more complex over-the-horizon mission profiles.

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