RELAY CONNECTIVITY IN HIGH INTERFERENCE ENVIRONMENTS THROUGH DEPLOYABLE ULTRAWIDE BANDWIDTH WIRELESS NODES

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ABSTRACT

This paper describes an Unmanned Ground Vehicle (UGV) system designed to navigate and map unfamiliar high interference and wireless obstructing environments. The UGV utilizes LiDAR for local area mapping, a camera for video feed, and houses a node deployment mechanism.

The nodes deployed are self-sufficient, low-cost, AA battery-powered, seamlessly connect over RF for data transmission, and integrate a Passive Infrared (PIR) sensor for proximity awareness. Each node is controlled by the Nordic nRF52840 System-On-Chip (SoC) with a mounted Qorvo DWM3000 Ultrawide Bandwidth (UWB) wireless module. The half-duplex DWM3000 was released by Qorvo in 2020 and has the potential to be used for various mobile, consumer, and industrial applications given its size and low power usage.

The remote interface displays the video feed from the UGV, a local view of the mapped area, a larger view of the entire mapped area, and a catalog of all PIR sensor information. The most challenging aspect of implementation is seamless node data transmission. The half-duplex nature of the communication brings the traditional hidden and exposed terminal problems, requiring some coordination between the nodes' transmission and reception periods.‘

INTRODUCTION

Remote control of UGVs or other robots over wireless is seldom uninterrupted, especially in high interference or obstructive environments. Frequent disconnections is commonplace, and there is seemingly no absolute solution for strong connectivity other than a wired connection. Inspiration can be taken from home wireless internet signal boosters, where the extended connection range comes at little cost to performance.

To enable a continuous wireless connection in obstructive environments, we designed deployable UWB RF nodes that connect for seamless communication through a node network. When deployed, the nodes create a network that links the UGV to the Remote Station. Through this link, the UGV transmits image and LiDAR map data to the Remote Station, and movement control is transmitted back to the UGV, including the signal to deploy new nodes. Data transmission over our UWB nodes is half-duplex, so we designed a transmission protocol for sending such data as quickly and reliably as possible given our limitations.

PROJECT OVERVIEW

Our project consists of three primary systems: the UGV, the Node Array, and the Remote Station.

The UGV, which is a modified AION R1 UGV Rover, is equipped with an attached LiDAR module, night vision camera, Nordic nRF52840 with a connected DWM3000, a servo controlled node deployment mechanism, and a Roboclaw drive controller. All processes are self-contained as ROS nodes, and interact with each other with ROS messages where necessary. ROS core runs on the onboard Nvidia Jetson TX2.

Whenever there is communication between the UGV and Remote Station, it is carried through a chain of nodes deployed by the UGV. Each node consists of a PIR sensor and a custom 4 layer PCB. PCB dimensions are 63mm by 68mm, making nodes small and portable. Key components of the PCB are the mounted DWM3000 and the nRF52840 MCU.

The Remote Station uses a Nordic nRF52840 with a connected DWM3000 to receive messages from the node array. It displays the camera and LiDAR map images received by the UGV. To direct the UGV's movement and actions, a USB-connected controller is used. Similar to the UGV, all processes are self-contained as ROS nodes, and a second ROS core runs on the Remote Station.

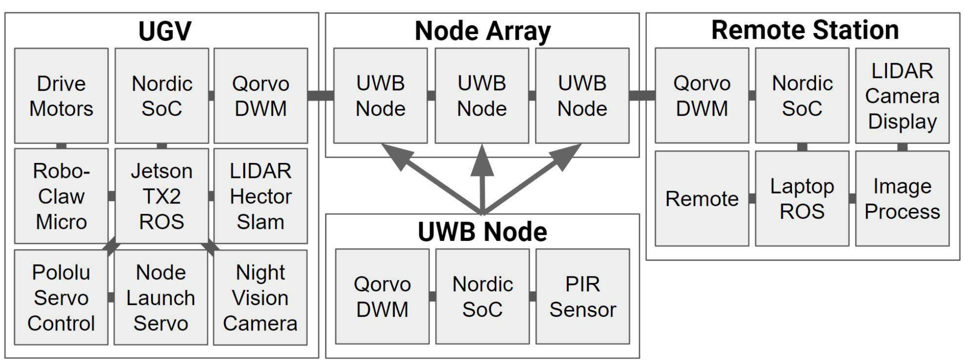

Figure 1: System Block Diagram.

ULTRA-WIDE BAND COMMUNICATION

Ultra-wide band communication is explored as a possible solution to fast and reliable communication with our UGV. UWB is radio communication that works through narrow RF impulses as opposed to amplitude or frequency modulation with a more traditional sinusoidal shape. Its fre-

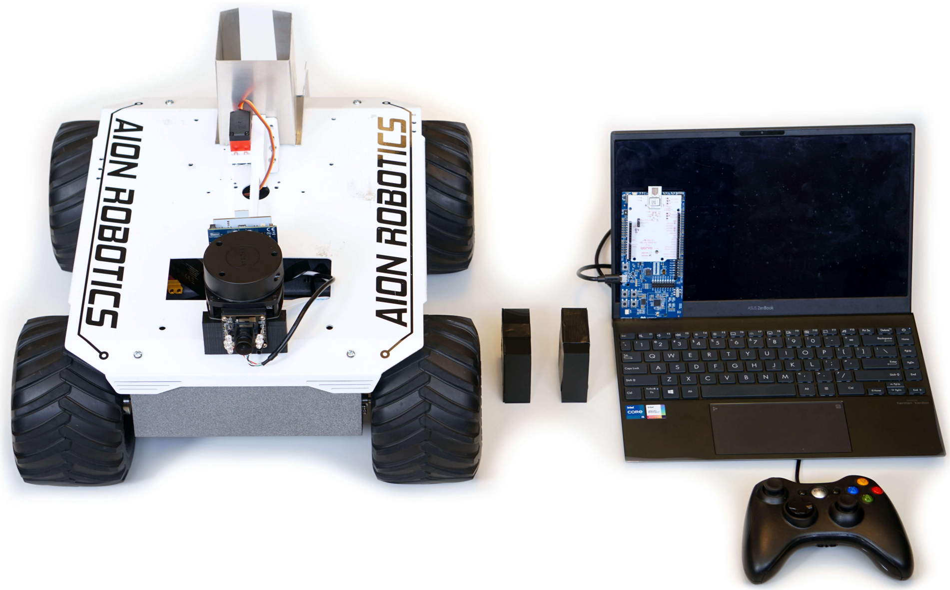

Figure 2: Systems with Nodes Deployed.

quency range is from 3.1 GHz to 10.6 GHz, with the existence of a sub 1 GHz frequency. The channel bandwidth is at minimum 500 MHz and capable of reaching up to 1.3 GHz [1].

For the purposes of this project, we were interested in UWB's high data rate, low power consumption, and low cost [2]. Our specific UWB module supported data rates from 850 Kbps and 6.8 Mbps, which was sufficient to transmit map data and compressed images. This is only a fraction of the maximum possible data rate that UWB is stated to support. For example, Multi-band OFDM with UWB is stated to support rates up to 480 Mbps. This rate can reach the Gbps range when combined with multi-level modulation techniques [3].The low power aspect of UWB was desired due to our system being powered by two AA batteries and expected to last for a moderate amount of time for real world applications. Since the nodes were planned to be only deployed and not retrieved, a low cost technology was necessary.

ROS DATA TRANSMISSION OPTIMIZATION ON UGV AND REMOTE STATION

The primary consideration made when implementing ROS on both the UGV and Remote Station was simplicity of design and compactness of network messages. These are conflicting goals, because increased project simplicity means less possibility of compacting features. However, as ROS abstracts processes to simple input and output messages, the requirement for simple data transmission is achieved despite the implementation of data optimization and other features.

Evident by the project setup, it is required that the following information be sent over the network: Camera stream, LiDAR data for mapping, UGV control data, Node deployment and initialization requests, and PIR sensor data. All of these data types can be condensed into two different ROS message types: `CompressedImage` of size less than 3kb, and a `StampedTwist` of negligible size.

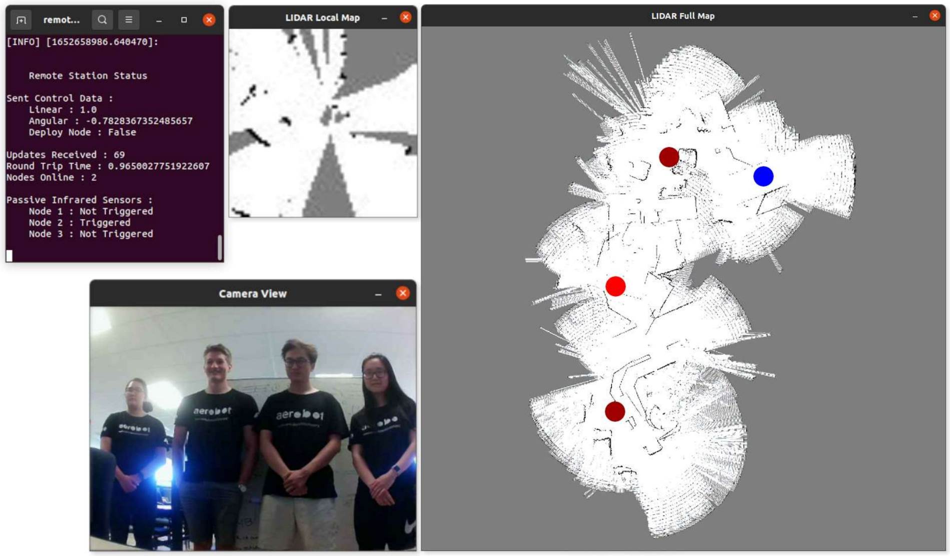

Figure 3: Remote Station Display.

A. UGV to Remote Station

Camera streams and LiDAR map data are both heavy transmissions sent from the UGV. The former being a large muti-dimensional array of RGB pixels, and the latter a volume of laser scans collected by the sensor. The transmission of this data at significant rates is not possible given the DWM module speed. However, with some tweaks to the way these messages are sent, it is possible to reduce transmission sizes to a fraction of the naïve implementation and increase project simplicity.

As the UGV is equipped with an Nvidia TX2, there is significant processing power which can be utilized to offload work from the remote station and complete in the field. With the camera images, full-resolution images can first be taken from the environment and shrunk, leveraging pixel averaging. Image compression can then be applied, reducing the message to a fraction of original byte size. This is accomplished with the `compressed` image transport republisher to get the `CompressedImage` message type. This pipeline is shown in figure 4, starting from node `usb_cam`. Data can be further compacted with the removal of header information from the `CompressedImage` message to get the raw `uint8` array for transmission, then serialized and sent on the node network. With these modifications the final camera image, shown in figure 3, takes a size of less than 3kb compared to the initial 100kb.

The LiDAR pipeline starts with scan data from `rplidarNode`, and directionally filtered to avoid erroneous data. The output is used by the Hector SLAM algorithm for mapping and localization. Instead of sending this map over the network for rendering on the Remote Station, rendering be performed on the UGV. Rendering is finalized with the `map_to_image_node`, which also uses the `pose`, or position, of the UGV in the map to acquire the local map. Similar to the camera image, this map image can be compressed to the `CompressedImage` message type and stripped, meaning a final size of less than 1kb. This pipeline is shown in figure 4.

Through simple and intuitive changes, an unwieldy pipeline of camera image and map data transmission can be easily accomplished within the limitations of the DWM module, and simplified

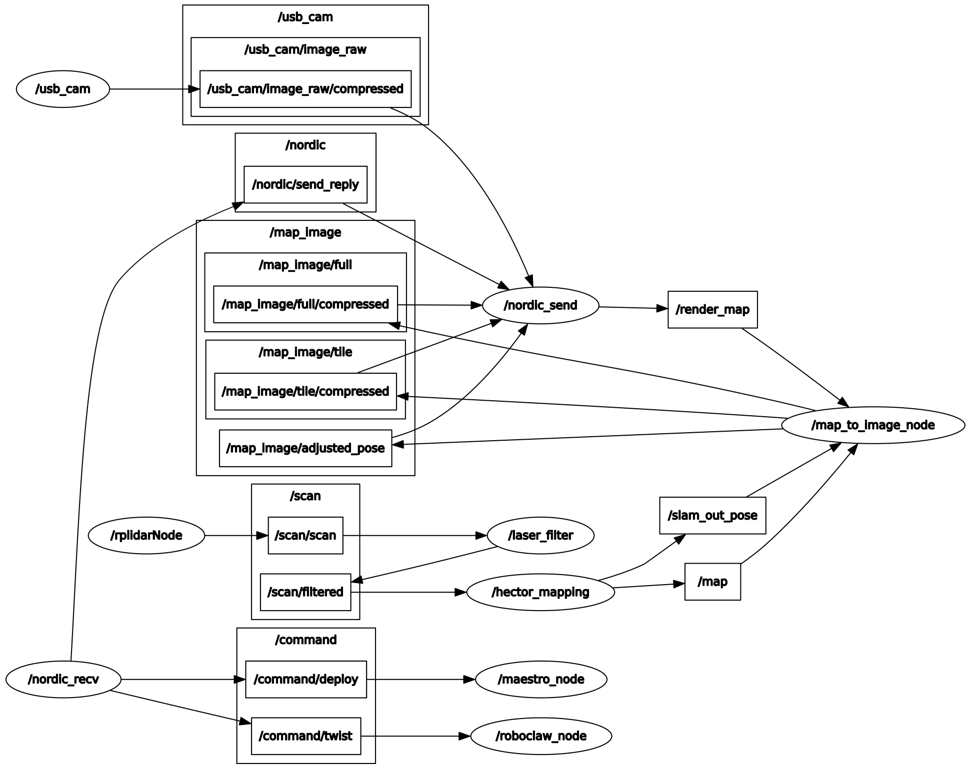

Figure 4: RQT Graph on UGV.

to a single message type `CompressedImage`. Sending the entire map is costly for the network, so during movement operation the compressed `tile` map is sent, which is a small area around the `pose` of the UGV. During node deployment, the UGV does not move or gather new data, so this opportunity is used to send the entire `full` map, which is also a `CompressedImage`. The `pose` of the UGV is converted to image space on topic `adjusted_pose` and sent during all `tile` and `full` map transmissions, so that the Remote Station can show the UGV on the full map and all the deployed node/PIR sensor locations during movement operation.
As the PIR sensor data needs to move in the same direction of the images, this information can be appended to the serialized `CompressedImage` as raw `uint8` bytes during transmission, and unpacked on the remote station as a string of bytes. When unpacked, this sensor data is displayed in the `UGV Status` window. It also updates all of the the PIR locations on the full map with a colored indicator of activation, such that the Remote Station operator can visualize where the PIR sensors are being triggered.

B. Remote Station to UGV

UGV control and node deployment are non-trivial processes on the UGV, but they can be simplified to a single message over the network.

The UGV drive system was modified to remove a GPS signal requirement with the consideration of our intended environment, and is controlled directly with the Nvidia TX2 over serial with the abstraction of a `Twist` message. This message which contains a linear and angular

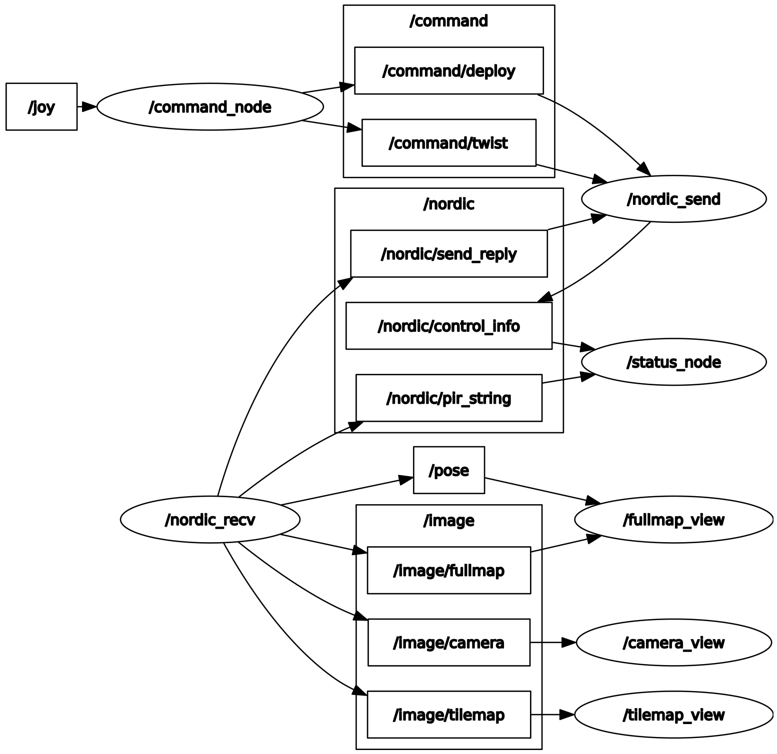

Figure 5: RQT Graph on Remote Station.

vector with float values in three dimensions, commonly used for robot control. Similar to the `CompressedImage`, there is great versatility in the way the `Twist` can be used.

Node deployment requires servo motion on the UGV and a broadcast of activation to other nodes, but this process can be handled on the UGV given an activation flag. The message type `TwistStamped` can be utilized, which adds a customizable header to the `Twist` message for this flag, and split post-arrival. With less than a single frame of 64 bytes, this package contains the data necessary to vary the speed of the UGV and indicate initiation of sub-processes when a node is needed to be delivered. This pipeline is shown on both figure 5 and 4.

HARDWARE

The development board nRF52840-DK was chosen as the microcontroller works well for wireless IoT applications due to its low-power feature and the support of Bluetooth 5 [4, 5, 6]. The nRF52840-DK has connectors with the Arduino Uno Revision 3 standard, which is compatible with many third-party shields [5], meaning no hardware modifications are required to interface with DWM3000.

Printed Circuit Board

The addition of the DWM 3000 EV module to the nRF52840-DK constitutes a node size too large when considering the deployment of many nodes by the robot, so we designed our portable

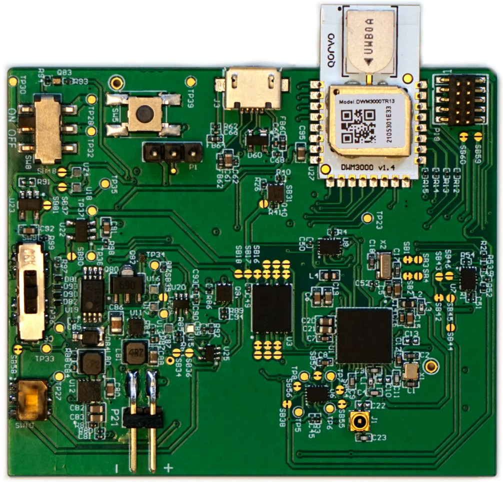

Figure 6: Printed Circuit Board.

nodes based on the nRF52840-DK. The original development kit consists of two MCUs: an nRF52840 MCU and an interface MCU for programming and debugging. Due to the shortage of the interface MCU, we removed the programming chip and kept the debug port for software installation. We used an external nRF52840-DK board as a debug probe to load software onto our nodes. Our node was also designed to be powered by either USB or an external battery. It has a 3V buck regulator and a 5V boost regulator, and it can take input from 1.7 V to 5.5 V. The DWM 3000 chip is mounted on our PCB, and it interfaces with our MCU through SPI. Additionally, we have 3 dedicated GPIO pins for the proximity infrared sensor.

COMMUNICATION PROTOCOL

With UWB communication being wireless and half-duplex, it was challenging to coordinate the nodes' TX and RX phases. Since reliability is a desired trait for this project, we created a protocol that employs acknowledgements and re-transmissions to achieve this reliability.

Our protocol, appropriately named the 'double-ack protocol', uses two `ACK` statements to coordinate the sending and receiving of data. The consideration was data transmission in a uni-directional sense; when data is transmitted to the relay node, the relay node responds with an acknowledgement upon successful reception. The relay node can pass data to the next node, which will also send back the first `ACK`. Knowing that the message was transmitted successfully, the relay node can send the first node a second `ACK`. This second `ACK` signals to the node that it can send the next part of the message. In summary, the the first `ACK` signals the successful reception of data and can trigger the transmission of the second `ACK`, which indicates that data transmission can continue. To support bidirectional data transmission, `RTS` and `CTS` were added. When a `CTS` is received at the relay nodes, the nodes set the direction of transmission.

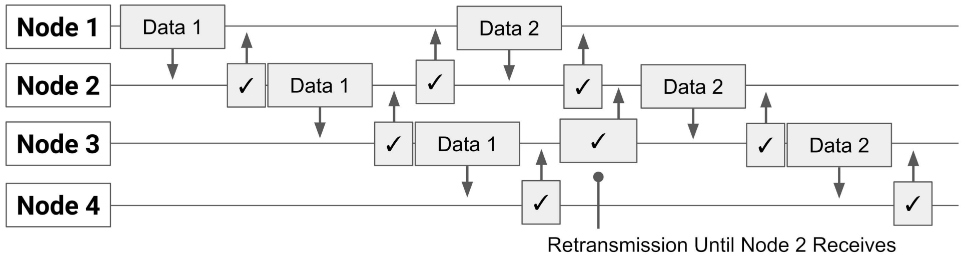

Figure 7: Double ACK Protocol Timing Diagram.

The primary benefit of the protocol is that multiple portions of the node network can TX and RX independently, creating a pattern of cascading transmission. In early stages of protocol development, the concern with using a single `ACK` was the delay of propagation through a large node network before sending the next message. If acknowledgements were sent between the nodes, the node would still have to wait for a period of time in order to ensure that the next node is listening for a transmission. With a second `ACK`, the node is informed when the next node is ready for data.

Something to consider when using the protocol is the overhead that comes with using two `ACK`s per frame. Because of this, a larger data payload is recommended to reduce the relative overhead.

DATA RATE

With the combined improvements in efficiency to the data transmission of images and transmission protocol program, we have achieved a range of 1 to 3 frames per second of camera images on the Remote Station. The tile mapping images and control data are much smaller than the standard camera image, meaning our round trip time ranged from 0.3 to 1 second depending on number of nodes deployed. As the UGV moves slowly for Hector SLAM mapping and reliability purposes, this frame-rate is suitable for our purposes in the intended environment. Additionally, movement commands from the Remote Station to the UGV are almost instantaneous due to insignificant size, therefore there is high responsiveness of motors.

CONCLUSION

This paper discussed the implementation of remote UGV control with deployable UWB nodes with the goal of fast and reliable data transmission. In our efforts to coordinate half-duplex communication, we have designed a functioning transmission protocol. Our project shows that such a system is possible and functional. There could be significant improvement made to the implentation of node networking and data optimization to further improve data rate and application speed.

Ultra-wide band was defined by the FCC in 2002 [1] and was used in by the military before then. Recently, UWB has gained attention from the community and corporations have come together to research and develop UWB, seeing its potential in communication, security, and location-based services. This project explores a fraction of UWB's potential usage and functionalities.

RESOURCES

Nordic Serial and Decawave Communication Controller
`https://github.com/eric334/nrf_com_controller`
UGV ROS Catkin Workspace
`https://github.com/eric334/robot_ws`
Remote Station ROS Catkin Workspace
`https://github.com/eric334/remote_ws`

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