

Interprocess Communication for Robotics Applications

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Abstract—Modern robotic systems are developed as a collection of independent processes. For these processes to function together, an interprocess communication system (IPC) must be implemented. Many prebuilt systems are available and this paper presents four popular options (Sockets, ZeroMQ, ACH, and ROS) as candidates for robotics. An analysis is presented for each based on communication latency and design metrics as applied to robotics.

I. INTRODUCTION

As modern robotic systems grow in complexity, it becomes increasingly beneficial to implement a multi-process control system. This provides a modular system architecture. A modular architecture protects the overall system from individual components failing. Critical system processes can be allocated additional resources to ensure continued operation during a partial system failure. By predefining the inputs and outputs for each subsystem, multiple teams of designers can use differing languages, allowing for optimization of each task. Additionally, the overall system can be distributed across a variety of hardware (full computers, single board computers, microcontrollers).

Many IPC options are available to designers and each must be evaluated on a per system basis to determine the best candidate. This paper will focus on evaluating several mainstream options and how they apply to design metrics of robotic systems. As robots operate in real time, the latency and data integrity of each communication step is of critical importance. For complex systems (humanoids, robots operating in proximity with humans, etc) with multiple processes running concurrently, communication delay can result in actuators responding to obsolete data. This paper serves to provide a guide to evaluating the capabilities of Sockets, ACH, ZeroMQ and ROS.

II. BACKGROUND

A. ACH (Shared Memory)

Shared memory offers the fastest read/write speeds for communication between processes within a single computer. As part of the POSIX¹ IPC library, shared memory is available to virtually every robotic system. Real time robotics require that the IPC system be able to prioritize the most recent data over data received sequentially (non head of line blocking). Basic shared memory provides this by overwriting variables but is susceptible to synchronization issues and all previous data is now lost[1].

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¹POSIX: Portable operating system interface. A set of standards for maintaining compatibility between operating systems.

ACH² builds on basic shared memory and provides a message bus (channel) between multiple writers and multiple readers. An ACH channel consists of a data buffer and an index buffer that are stored in a shared memory file. The channel provides synchronized access via a mutex and a condition variable. This allows for priority inheritance and prevents starvation[1]. The ACH library is open source and formally verified[1] making it suitable for widespread use.

ACH channels provide high levels of flexibility in communication and programming. They can be configured to read the most recent data or in order it was received. A read command can block until data is received or it can poll the channel as needed. Figure 1 below is an example of an ACH based control system for the Hubo robot.

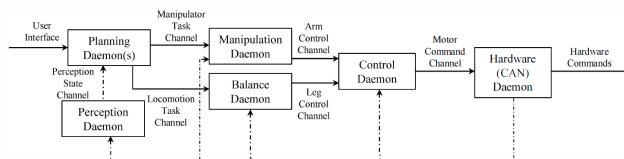


Fig. 1. ACH Communication Flow Chart for HUBO Robot

ACH provides LAN based communications by utilizing sockets messages to transport channel data. Each system running the ACH network daemon (ACHD) can write directly to remote shared memory resources connected to the network[2]. This allows for CPU intensive processes to be offloaded from the robot to a local high performance computer.

B. Sockets: TCP and UDP

Sockets provides interprocess communication over a network via the TCP (Transmission Control Protocol) and UDP (User Datagram Protocol). It is built into most operating systems which makes code highly portable. Sockets communicate with a client/server architecture with either point to point or multicast messages[3]. Utilizing IP addresses and existing internet infrastructure allows processes to communicate with remote locations. This makes it possible to quickly and cheaply connect the robot to sensors, controllers, and embedded systems. As part of the POSIX library, sockets allows many different operating systems and programming languages to communicate with no extra software. Modern network routers offer gigabit connections enabling sockets to provide fast communication between distributed processes.

²Available at <https://github.com/golems/ach>

Sockets message buffers are head of line blocking and disregard new messages when full. This is problematic for robotics where sensor data is of critical importance.

1) *TCP*: TCP offers robust messaging between a single client and a single server process. Initial handshaking is required during connection and can cause additional latency for the initial message[4]. Each message transmission triggers a response from the recipient. This allows TCP to identify dropped messages and retransmit. While good for data integrity, response messages and retransmission increase latency.

2) *UDP*: UDP offers one quick directional communication between processes. UDP supports client/server and multicast topologies. Processes are bound to IP address(s) and port number(s)³. There is no handshaking or direct link between the processes. This allows multiple clients to send data to a single server. UDP inherently has less latency than TCP due to its 'fire and forget' approach to messaging. Data integrity suffers as there is no way to identify missed messages. This method favors transmission speed and has less latency than TCP.

C. ZeroMQ

ZeroMQ⁴ (MQ) is a messaging system that extends on the foundations of sockets. It provides additional functionality to TCP by sending messages to a system topology instead of specific IP addresses. MQ prevents sending to specific IP addresses by design. The available messaging patterns is open ended. Common patterns include publish/subscribe and request/reply. Figure 2 below shows examples of how topologies can be arranged.

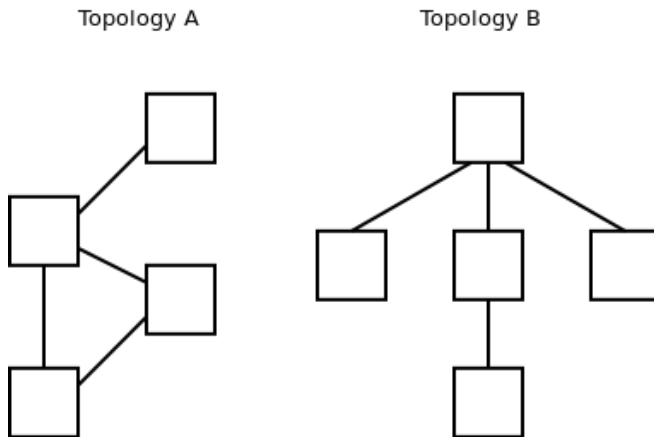


Fig. 2. ZeroMQ Example Topologies

Only one messaging pattern is allowed for a topology and they cannot be interconnected. This guarantees that data will arrive at their intended location(s). MQ separates its stack into end to end and hop by hop layers. Unlike TCP/IP, each MQ end to end protocol has its own hop by hop protocol[5]. This allows each specific messaging pattern to have their

³Multiple IP addresses and port numbers only available for a multicast UDP socket

⁴Available at www.zeromq.org

own routing functionality. Bidirectional messages can be sent to specific nodes in the topology. Each intermediary node can determine if downstream sections of the network are unreachable and can signal the original client to resend now or wait until connectivity has been reestablished.

MQ provides synchronization for data in multithreaded applications. This functionality is hidden from the developer and allows for complex, scalable messaging in multithreaded systems. Common methods for dealing with synchronization (mutex locks, etc) can block threads when scaled to high number of processes. MQ abstracts complex lock free synchronization methods behind the familiar interface of sockets[6].

D. ROS

ROS⁵ (Robot Operating System) is a flexible framework for developing robotic systems. Offering more features than an IPC, ROS utilizes TCP as its core transport mechanism for communication between processes. In addition to the IPC, ROS offers a wide library of prebuilt tools and a vast user base from which to draw on modular solutions that can plug into any ROS system. This reduces development time and amount of low level code that needs to be written for each piece of hardware. Figure 3 below shows an example ROS network diagram.

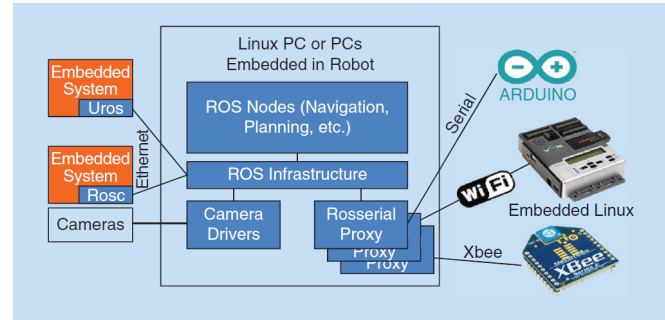


Fig. 3. ROS Example Network Diagram

Commerically available embedded systems can interface with the ROS system by adding interface processes (ROS topics) to the core system. ROS was designed to support higher level robot functions instead of the control of individual motors/sensors/etc. Integration of subsystems is left to the designer as ROS does not support fieldbuses[7]. ROS can be implemented as a combination of an embedded PC, proprietary systems with custom interfaces, and ROS Messaging. Embedded PCs provide smooth ROS integration but fail to offer hard real time support. Existing robots can be managed from ROS through topics acting as translators. This abstracts the lower level programming and allows for the existing systems to operate in real time. The IPC system for ROS operates on remote procedure calls and publish/subscribe protocols for messaging.

The ROS IPC system allows for custom messages interface with embedded systems. Rosserial, rosc, and Rosbridge are

⁵Available at www.ros.org

methods of passing these messages. Rosserial provides a proxy over a C++ client that can be ported to any system that supports the language. Rosserial provides a ROS-like API to publish, subscribe, offer and consume RPC services over serial. The proxy can act as a bottleneck increasing message latency. Rosc allows for direct connection and messaging to systems supporting C, but TCP/IP overhead can overwhelm low level peripherals. Rosbridge allows dynamic socket and websocket access to the full capabilities of ROS[7].

III. TEST PROCEDURES

In order to evaluate each of the discussed IPC methods, a test system was developed that incorporated a laptop, 100mbps wired network connection, a Raspberry Pi single board computer (SBC), and an OpenCM9.0 microcontroller board designed for command and control of dynamixel servomotors. The system transports messages over ethernet, serial, and USB. For consistency, the serial link was set to the same baud rate (9600) as the USB link. The objective of this test was to measure the round trip latency of a message by utilizing each of the aforementioned IPCs. Only one communication link (Link 1 or Link 2) varied for each test and UDP was selected as the control for the other. Figure 4 below shows the overall system diagram of the test setup.

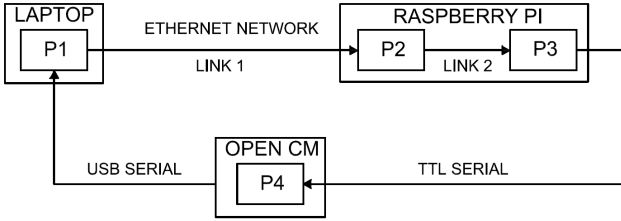


Fig. 4. Test Setup Block Diagram

Process P1 generates a random one byte message send sends the data over the network to process two. P2, P3, and P4 all have blocking read functions and immediately pass the message on to the next. This was done to simulate a more complex system while minimizing processing delays from the results. P1, P2, and P3 are written in Python while P4 was written in its native Arduino code. P1 utilizes the most accurate time function available to python. 10000 samples were processed for each test.

The objective was to simulate each IPCs ability to receive, process, and act on incoming sensor data. To accomplish this, the test was designed to send single byte messages at a high enough frequency to emulate sensor data without overloading each processor. As noted in the test results seen in prior research[1], the initial communication of TCP can cause a spike in message latency. To eliminate this impact from our data we utilize a test message that must be successfully received prior to the start of data logging.

IV. TEST RESULTS

A. Results Summary

After completion of all testing, no IPCs dropped any messages during transit. This can be attributed to the ideal testing conditions. Hardwired network communication and single byte package size allowed for both TCP and UDP packets to be received despite UDP's lower inherent reliability. The introduction of a wireless networks or lower quality routers may cause more of a differentiation to arise. The fastest overall system consisted of UDP network messages and ACH messages for the internal communication through the Pi. There was negligible difference in transit time between TCP and UDP over the network. Similar delays at this stage of the test can be attributed to the routers throughput. TCP response messages are processed at or below the microsecond accuracy level and does not impact our test results. A summary of all data collected is presented below for the network link in Table I and the internal Raspberry Pi link in Table II.

TABLE I
RESULTS SUMMARY: NETWORK LINK

Item	Network: Link 1				
	UDP	TCP	ACH	ZMQ	ROS
Average (ms)	3.834	3.829	ZMQ	N/A	ROS
Min (ms)	3.359	3.399	ZMQ	N/A	ROS
Max (ms)	95.063	42.006	ZMQ	N/A	ROS
Std Deviation (ms)	1.441	0.768	ZMQ	N/A	ROS

TABLE II
RESULTS SUMMARY: RASPBERRY PI LINK

Item	Raspberry Pi: Link 2				
	UDP	TCP	ZMQ	ACH	ROS
Average (ms)	3.834	4.774	ZMQ	3.752	ROS
Min (ms)	3.359	4.079	ZMQ	3.219	ROS
Max (ms)	95.063	43.974	ZMQ	73.533	ROS
Std Deviation (ms)	1.441	1.160	ZMQ	1.705	ROS

B. UDP Results (Control)

The control of this experiment utilized UDP messages over the network and UDP messages sent to the loopback address on the Pi. No missed messages occurred despite UDP being the least reliable IPC method tested. Consistent results occurred with a standard deviation of 1.441 ms and the average transit was 3.834 ms. This was the second fastest configuration tested. Figure ?? below shows a summary of collected data with outliers removed for clarity.

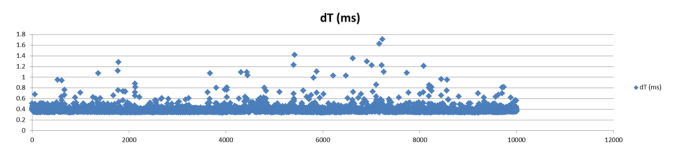


Fig. 5. UDP Control Test Results

C. TCP Results

TCP was tested in both Link 1 and Link 2 configurations with UDP as the second link. No missed messages were recorded as expected for TCP. For the network link, TCP performed with negligible difference to UDP. This would suggest that for small data packets and reliable network connections the additional delay incurred by TCP's response message is negligible. Figure ?? below shows a summary of collected data with outliers removed for clarity.

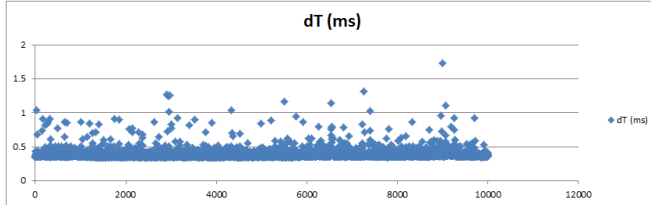


Fig. 6. TCP Link 1 Test Results

Differentiation arises when TCP is utilized for the Link 2 loopback transport. Additional latency was recorded for an average transit time of 4.774 ms and a standard deviation of 1.160 ms. This suggests the additional TCP overhead becomes an issue for embedded systems and would not be a valid candidate for an internal IPC. Table ?? below summarizes the Link 2 test results.

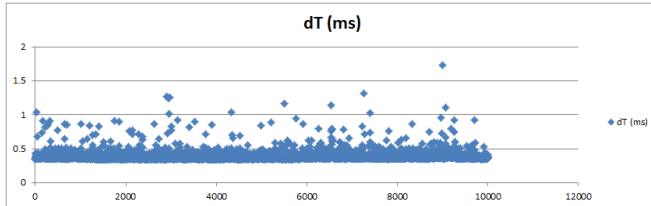


Fig. 7. TCP Link 2 Test Results

D. ZMQ Results

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E. ACH Results

ACH performed the fastest of all IPC methods tested. For consistency, UDP was used as the Link 1 transport over the ACHD library. ACHD can be configured as TCP or UDP messages and it was concluded that similar results would have been produced. Average transit time was 3.752 ms with a standard deviation of 1.705 ms. ACH exceeds the speed of UDP when transmitting internally and has the synchronization benefits of ZMQ without the additional latency observed. Figure 8 below shows a summary of collected data with outliers removed for clarity.

F. ROS Results

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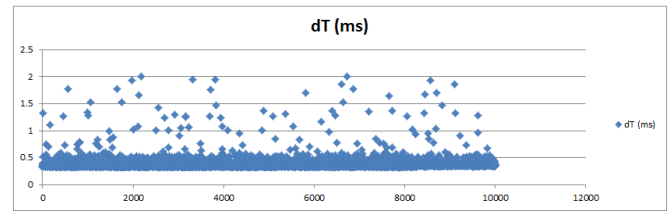


Fig. 8. ACH L2 Test Results

V. IMPLEMENTATION

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VI. CONCLUSIONS

conclusions placeholder

ACKNOWLEDGMENT

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