Proxying ROS communications — enabling containerized ROS deployments in distributed multi-host environments

Arne Wendt¹ and Prof. Dr.-Ing. Thorsten Schüppstuhl²

Abstract—With the ability to use containers at the edge, they pose a unified solution to combat the complexity of distributed multi-host ROS deployments, as well as individual ROS-node and dependency deployment. The bidirectional communication in ROS poses a challenge to using containerized ROS deployments alongside non-containerized ones spread over multiple machines though. We will analyze the communication protocol employed by ROS, and the suitability of different container networking modes and their implications on ROS deployments. Finally, we will present a layer 7 transparent proxy server architecture for ROS, as a solution to the identified problems. Enabling the use of ROS not only in containerized environments, but proxying ROS between network segments in general.

I. INTRODUCTION

Software containers as a technology gained traction mainly as a solution to problems encountered in cloud computing. [1] Providing isolation between processes and their environments, they enable lightweight multi-tenancy and efficient resource sharing. [2] Current container technology does offer more though (compare e.g. [3]): Applications with all their dependencies (services, configuration, etc.) can be bundled as a single artifact, seriously simplifying deployment processes. Shipping all dependencies bundled within one artifact, further allows for greatly simplified (even immutable) infrastructure – a host with just a container runtime – reducing host-deployment and -maintenance efforts. With interoperable container runtimes being available for all major operating systems (OSs) (Linux, Windows, OSX), a containerized application can be deployed virtually independent of the host machine and OS.

Apart from the increased security through process- and usually additional network-isolation from the host machine, especially the benefits in deployment and cross-platform compatibility have made containers (and docker especially) a tool for reproducible deployments not only in cloud computing, but research in general, as proposed in [4], and even robotics research in particular, as proposed in [5]. As identified in [6], a major advantage of bundling dependencies in robotics development lies in consistently reproducible deployments of even cutting edge algorithms and software modules, not available as stable distributions through package management systems.

ROS as a framework enables the composition of robotics applications as distributed systems on heterogenous hard-
networking at [16] is not existent. While [17] devotes a whole chapter [6] to docker, networking outside a single host is not covered, though the author proposes docker swarm networking for connecting multiple hosts at ROSCon 2015 [14].

While acknowledged as a tool for establishing reproducibility in robotics applications, we can mostly find publications on benefits of using docker with ROS in academic use cases and descriptions of uses in education like [5], [18]. While we can find [19] as a solitary example, publicly available works using docker with ROS for distributed deployments seem sparse. None of the above examples exhibits and covers the challenges of building distributed ROS deployments with containerized nodes. As we will discover in section III the challenge in containerizing ROS nodes is a communications problem. We will thus briefly consider works combining cloud computing with ROS, as the encountered problems from network partitioning are assumed to be similar. While in [20] an OpenStack-based cloud is used for data processing and storage, this cloud is a local deployment on the same network as the remaining nodes, thus not incurring any problems of traditional cloud computing. We can find an actual cloud computing setup in [21], overcoming network boundaries by using robridge an a custom cloud bridge. Apart from robridge – identified as the most common tool to enable cloud robotics applications with ROS by [22] – we can find ROSLink [23] as another tool to solve the problem of connecting ROS applications over multiple network segments. All these solutions do not behave transparently for a ROS deployment, but have to be interfaced explicitly with custom, application specific protocols.

III. DOCKER NETWORKING AND ROS

To understand the problems and limitations when using ROS in containers, we will first introduce the operating principle of the ROS middleware. With this foundation we will evaluate the fitness for containerized ROS applications of the currently available networking modes provided by docker.

A. ROS communications

The ROS middleware is composed of two different parts: An Extensible Markup Language Remote Procedure Call (XMLRPC)-based management protocol and the actual data transmission protocol TCPROS. Following we will analyze both protocols separately.

1) XMLRPC – Master- & Slave-API: ROS defines two XMLRPC-based Application Programming Interfaces (APIs) for management purposes; a Master- [24] and Slave-API [25]. XMLRPC uses the Hypertext Transfer Protocol (HTTP) as underlying transport.

a) Master-API: The Master-API is implemented by the ROS master. Its address has to be known to all nodes participating in a ROS network. Nodes consume this API to (un-) register topic publications and subscriptions, services, as well as performing topic-, service- and node-information-lookup.

b) Slave-API: Each node provides a Slave-API. This API is consumed by the master as well as other nodes. Apart from querying runtime information about a node, the master consumes this API for management purposes like updating parameters and shutting down nodes, as well as to notify nodes about new publishers of their subscriptions. Nodes mutually consume their Slave-APIs to negotiate a communication channel for topic-data transmission; the subscribing node initiates the connection. A random TCP-port is allocated for the underlying HTTP server.

2) TCPROS: While ROS supports the negotiation of the protocol and implementation to use for data exchange, TCPROS is the only officially provided and supported protocol. TCPROS supports data exchange for topics and service calls; representing the last step and actual data exchange (4) in fig. 1. Per node usually one TCPROS endpoint is allocated on a random TCP-port, the connection is established by a subscribing oder service-calling node. In contrast to the XMLRPC/HTTP based management protocol, TCPROS does not include any routing information. [26]

B. Docker networking-mode fitness for ROS

We will cover the networking modes provided by a stock docker installation. While libnetwork – as provider and implementation of virtual networking in docker – does support plugins to extend its functionality, their deployment on host machines adds additional efforts, largely invaliding the motivation of containerizing applications. The available

1See section II-A.2 for limitations

Fig. 1. Order of communications in ROS: Advertising topic /chat by node talker and subscribing from node listener. Arrows showing direction of communications channel establishment, and XMLRPC method call and return value.

When registering, nodes report their slave API endpoint to the master, using an explicitly configured hostname or IP-address. A connection to consume the Master-API is initiated by a node.

Figure 1 shows invocation of the Master-API for the talker node, registering as publisher for the /chat topic. As step 2, listener calls the registerSubscriber method on the Master-API to register itself as a subscriber to the /chat topic, and retrieve a list of Slave-API-XMLRPC-endpoint-addresses of nodes publishing the topic.
network modes are documented in brief at [10]; while omitting ipvlan for unknown reasons, its documentation is available at [11]. Following, the need for bidirectional communication establishment as seen in section III-A will be the main focus of our discussion. Discussed networking modes will be bridged, host, ipvlan and macvlan, as well as overlay networking. Ipvlan and macvlan target the use case of connecting containers to external (outside the host machine) networks. For these networking modes we will therefore as well discuss the stock IP-address management (IPAM) mechanism and behavior, as these impact the integration mechanisms of containers in external networks.

1) Bridged: Bridged is the default network mode used by docker. The operation principle is shown in fig. [2]. A network bridge br is created on the host machine host A/B. The virtual network interfaces eth0 of containers container A/B connect to the bridge acting as a network switch. Connectivity from the containers to an external network segment is provided by a router, performing Network Address Translation (NAT) between br a host network interface (e.g. eth0). Each host can communicate with all containers running on that host, e.g. host A with container A, and host B with container B. As the host performs NAT routing, containers can reach all network targets on external network the host itself can reach, e.g. container A can reach host A and host B. Containers, being located behind a router, are not directly reachable from the external network, e.g. host A and container A cannot reach container B. Exposing applications from within a container to the external network is performed by forwarding ports from the host to the container. This technique is shown for host B and container B: Forwarding port 80 from the container to port 8080 on the host machine, allows participants on the external network to access a service on port 80 in container B by connecting to port 8080 on host B.

ROS requires bidirectional connection establishment, which is not directly satisfiable using bridge networking. As described in section III-A, the ports allocated for communication by ROS are chosen at random. This behavior prohibits the use of port forwarding to make containerized applications available to an outside network segment, as the ports to forward are not deterministic and not know a priori. Thus, using bridged networking, it is not directly possible to connect containerized ROS nodes to nodes on an external network.

2) Host: Using host networking mode does not allocate virtual network interfaces within a container, but grants direct access to the host network interfaces from within a container. Tough it does technically allow ROS nodes to be ran inside a container and communicate with nodes on an external network, we evaluate host networking to not qualify as a universal solution for the following reasons: It removes network isolation and thus a major portion of the benefits of containerizing applications, and it is no portable solution as it is only available on Linux based system [27].

3) ipvlan & macvlan: Ipvlan layer3-mode uses a similar setup to bridge networking, and exhibits similar behavior with the major difference, that reverse routing is technically possible when using static routes from the external network. Due to this similarity we will not consider ipvlan layer3-mode any further and scope the following analysis to ipvlan layer2-mode. Ipvlan and macvlan networking modes each allocate a sub-interface on an interface of the host machine, mapping this sub-interface into a container. While macvlan allocates an additional MAC-address on the interface, ipvlan does only allocate an additional IP-address. In each case, a container gets direct access to the network of the underlying host/parent interface, while retaining host and container network isolation and allowing members of the external network to reach containers as if they were physical hosts.

While both networking modes – ipvlan layer3-mode and macvlan – do in theory provide an optimal solution in terms of enabling direct network access for containers, they do come with a caveat though: IP-address management.

a) IPAM: Networking in docker is implemented using libnetwork. Each networking mode is implemented by a driver [28]. A driver is responsible for all aspects of network-operation, including IP-address management (IPAM). IPAM in turn is implemented by IPAM-drivers, owned and controlled by an instance of a network driver [28], [29]. The available default IPAM-drivers shipped with docker do assign addresses from either a random or user-defined subnet, but do not support address assignment using Dynamic Host Configuration Protocol (DHCP). Using macvlan/ipvlan networking on multiple hosts on the same network requires synchronization of subnets to guarantee connectivity, and synchronization of disjoint address-pools to avoid address conflicts, over all hosts; adding management efforts and an additional problem of configuration distribution among hosts.

While a third party network driver with DHCP support is available at [30], and an experimental DHCP-IPAM-driver
is available at [31], [32], we could not confirm them to be working on all OSs targeted by docker. As stated in section III-B, we do not consider plugins to be a viable universal solution (see section IV for further information). Based on the behavior of the stock IPAM-drivers we evaluate macvlan and ipvlan networks as not suitable for containerized ROS applications. We believe address management to be an issue to be tackled by either using DHCP, or while deploying the host machines and their operating systems, and not to be solved by manual configuration distribution at container instantiation time.

4) Overlay: Allows to build networks spanning multiple docker instances on multiple hosts, transparently connecting containers over host boundaries. While solving the problem of connecting containerized ROS nodes on multiple hosts, overlay networking does not allow to communicate with non-containerized nodes on different hosts and/or networks.

C. Problem Statement

Focusing on docker, as the container runtime available for the most common operating systems, from our analysis in section III-B, we can conclude, that no stock-available networking mode is suitable to run containerized ROS nodes, with our basic requirements:

1) nodes distributed among different machines
2) mix of nodes ran directly on host OS and containerized
3) no additional configuration distribution and management

While overlay networking allows to satisfy requirement 1, it fails to satisfy requirement 2 and 3. Macvlan and ipvlan networking can satisfy requirements 1 and 2, while failing to satisfy requirement 3 with the provided IPAM implementation (see paragraph III-B.3.a for details).

Consequently, we need to find a way to enable the use of ROS in containers, while being able to communicate between containerized nodes and nodes ran directly on the host OS, and removing additional out-of-band configuration and management. As out-of-band we want to classify all configuration an management that is not local to ROS and docker, or not supported by their distribution/deployment mechanisms; e.g. installing third-party plugins would be considered out-of-band, while pulling container images from a registry would not (see e.g. paragraph III-B.3.a).

IV. L7 ROS proxy

As the container runtime cannot provide a suitable solution by itself, we have to find a solution within the bounds of ROS and docker, on a higher networking layer.

With bridged networking and port forwarding, docker provides a networking mode with the ability to expose containerized applications on the network, with no configuration to be shared and managed among multiple hosts. As described in section III-B.1 the main problem of using bridged networking is the non-deterministic allocation of ports used for ROS communications. Finding a way to allocate all ports used for ROS communications from a deterministic port range, would provide a foundation to use bridged networking with containerized ROS nodes. Allocating and forwarding ports to the host machine would provide an additional benefit: Name- and address-resolution will be scoped to the network of host machines and not require routing rules and public (scoped to the network) name resolution services for containers. We will further require our solution to be transparent (i.e. no changes to node implementations and network configuration of containers) for all nodes; containerized or not.

A. Concept

As a solution we propose a proxy on the network, on the application layer (layer 7 / L7), ran in a separate container, with the capability of allocating all ports for ROS communication from a specified range to be forwarded to the host. The concept is shown in fig. 3. A proxy server rosproxy is ran in a container, sharing a bridged network with containers running ROS nodes. A set \{([m,n],o)\} of a port \(o\) and a range of ports \([m,n]\) from the proxy container will be forwarded to the hosts interface eth0 as ports \{[x,y],z\}. While containerized ROS nodes can connect directly to other nodes on the network using TCPROS, the rosproxy shall allow the reverse and proxy TCPROS communication from ports within the range \([m,n]\) to the relevant containerized nodes in containers node A/B. As seen in section III-A, the latter is required for all XMLRPC communications as well.

1) Proxying XMLRPC: Nodes report their XMLRPC-management-API to the ROS master, consisting of a randomly allocated TCP-port and either a hostname or IP-address (explicitly configured from environment variables

\[\text{XMLRPC} \rightarrow \text{TCPROS}\]

Fig. 3. Networking topology and connections, when using containerized ROS nodes with proposed rosproxy

[2] We will later find, that a proxy server provides additional benefits outside of containerization.
ROS_HOSTNAME or ROS_IP). To expose these API endpoints using the proxy, communication from nodes to the master will have to be intercepted (cmp. fig. 3), and the reported XMLRPC endpoints rewritten to the address of an endpoint provided by the proxy and reachable on the external network. Requiring interception and modification of nodes XMLRPC calls to the master, we can find a simple concept of transparently injecting the proxy server into the communications: The proxy server will be set as the ROS master address for all containerized nodes on a machine. On startup, nodes will register with the master. Configuring the proxy as the address of the ros master, we can intercept this communication. XMLRPC leveraging HTTP as transport protocol, allows to dynamically allocate an HTTP endpoint on the proxy per node, rewrite the nodes XMLRPC-API-address to this new endpoint, and proxy calls to this endpoint back to the respective node. As documented in [24], the calls reporting a nodes XMLRPC address (as caller_api), thus requiring interception and modification, are registerService, registerSubscriber, unregisterSubscriber, registerPublisher and unregisterPublisher. fig. 3 shows this behavior of relaying all XMLRPC requests from nodes through the rosproxy, as well as relaying all calls to the nodes slave APIs through the proxy. All ingress from the external network is over ports forwarded to the hosts network interface.

2) Proxying TCPROS: TCPROS itself does not contain any connection information and does not need any interception and data modification. To proxy TCPROS connections, a simple TCP proxy, forwarding traffic from a port on the host to the port allocated for TCPROS communications by a ROS node is sufficient. The TCPROS endpoint, as allocated by a node, is reported either on service registration (service_api when calling registerService on the master API [24]) or as a protocol parameter in response to a requestTopic call to a nodes slave API [25]. To effectively proxy TCPROS connections, these XMLRPC calls have to be intercepted as well; instantiating a new TCP proxy for each TCPROS port reported by a node, and rewriting the service_api or relevant ProtocolParam values in the XMLRPC call or response. As shown in fig. 3, outbound TCPROS connections from within a container are routed directly by docker, while inbound connections are proxied from ports forwarded to the hosts interface on the external network.

B. Implementation

Based on the above concept we can develop an architecture for an implementation of a rosproxy. The concept is shown in fig. 4. At runtime, the proxy will consist of multiple individual TCP proxies and multiple HTTP endpoints as XMLRPC proxies. A /master endpoint will proxy all calls to the master API from nodes on the internal network br. For each node (e.g. node /caller_id) a new HTTP endpoint will be allocated dynamically (e.g. /node/caller_id). This node specific endpoint will expose a nodes slave API via the proxy. For each TCPROS endpoint reported by a node, a TCP proxy – forwarding a port on the rosproxy host to the respective endpoint – will be instantiated. In addition to an HTTP endpoint, an additional TCP proxy will be allocated for each nodes slave API. All the resources allocated per individual node are shown enclosed by a gray dashed line in fig. 4. Lifetime of those resources is managed by counting a nodes subscriptions, publications and registered services, as well as cyclic “pinging” of the node, using its XMLRPC API. This resource lifetime management in combination with the additional TCP proxy for each nodes slave API enables support for stale node detection an registration removal, as implemented by rosnodes cleanup [33]. The internal handler functions for each HTTP endpoint will take care of allocating new endpoints and TCP proxies, and rewriting those addresses/endpoints in XMLRPC calls.

While the diagram in fig. 4 focuses on the operating principle and shows proxying of ROS communication from an internal to an external network, we can see the core
functionality enabling containerization of ROS nodes: The exemplary ports $p_1$ and $p_2$ can be allocated from a predefined range (e.g., $[x, y]$) in fig. 3 and exposed via the host. In the intended setup as shown in fig. 3, the `rospy` in turn has to use (and can be configured to do so) the hosts hostname or address for the reported and rewritten XMLRPC and TCPROS endpoints.

We implement `rospy` using JavaScript (ECMA Script), targeting the `Node.js` runtime. The implementation is available at [34].

V. CONCLUSION

We analyzed the networking-related challenges while containerizing ROS nodes in distributed multi-host environments for mixed deployment of containerized nodes and nodes ran directly on a host machines OS. Focusing on `docker` as container runtime, we provide a solution to the problem of bidirectional connection establishment, requiring no shared configuration management, no modification to a stock `docker` installation or changes to the underlying infrastructure and container host, by enabling the proposed proxy itself to be ran inside a container. Despite the focus on the `docker` runtime, the presented solution is runtime agnostic. We believe the work to be of great value by enabling fast and easily reproducible deployments of ROS systems on heterogeneous infrastructure, by leveraging containerization and container distribution mechanisms. Simultaneously lowering the maintenance and management overhead for these systems, as containers can ship all required dependencies.

While this work targets ROS and not ROS 2, we believe that enabling evaluation and research into containerized ROS deployments will deliver value beyond the lifetime of ROS and into ROS 2. The ROS 2 DDS/RTSP-based [35] transport and discovery may in the future lend itself to replicating similar setups as implemented and discussed here, by e.g. using DDS routing services as shown in [36].

While we set out to only enable containerization of ROS nodes, we effectively provide a solution to proxy ROS communication over network boundaries and between network segments in general. With this capability, we imagine the work to enable further research in cloud robotics, by enabling transparent proxying for ROS, using its native communication protocols and technologies.

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