Overseer: A Multi Robot Monitoring Infrastructure

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Abstract: In this paper, we present a lightweight runtime monitoring system for Multi Robot Systems, intended to supervise and identify the state of a team of robots. It integrates the Nagios IT monitoring tool and the ROS robotic middleware without any additional software at the robot side. The experimental results demonstrate that the proposed monitoring system has a negligible performance impact on the robot, and the monitoring server can easily support hundreds or even thousands of monitored robots.

1 INTRODUCTION

Robotics started at the beginning of 20th century, with the necessity to improve productivity and quality of manufactured products. Mobile robots are becoming ubiquitous, as they are used to accomplish a variety of tasks, from vacuum cleaning to accessing remote and dangerous places, for example (Dudek and Jenkin, 2010).

A cost-effective way to enhance performance and provide robustness to a robotic solution is to use multiple robots instead of a single robot. Multi-Robot Systems (MRS) have some advantages over Single-Robot Systems (SRS), such as reduced time required for task completion through parallelism, and increased robustness and reliability due to the intrinsic redundancy. An MRS of cheaper and simpler robots are typically more reliable than a more expensive and intricate single robot (Parker, 2008). On the other hand, MRS present more complex challenges compared to SRS. For instance, MRS are more difficult to manage and coordinate collectively, requiring increased communication capabilities. Another challenge is in determining the system's global state and debugging it, due to its distributed nature.

MRS can be classified as homogeneous or heterogeneous (Parker, 2008). Homogeneous MRS means that all members of the team have the same specification (hardware and software configuration). Heterogeneous MRS can have different kind of robots in the same team. The advantage of heterogeneous MRS is to support different kind of specialized and simpler robots, compared to a single robot model that does several different tasks. In this paper, we present a monitoring system for heterogeneous MRS, where the *goal* is to provide a means to easily monitor faults and the state of the MRS as a whole. This is achieved with the integration of the Nagios IT monitoring tool and the Robot Operating System (ROS) framework. The detection and isolation of the defective robot is a first step toward an adaptive MRS, which can execute the desired task even in the presence of faults.

The rest of this paper is organized as follows. Section 2 presents previous papers. Section 3 describes the proposed software architecture. Sections 4 and 5 present the experimental setup and the obtained results. Section 6 concludes the paper.

2 PREVIOUS WORKS

Parker (Parker, 2008) describes a large number of possible of faults in robotics, such as: Robot sensors faults, uncertain environment models, interaction faults, limited power and computation limits. In order to navigate this complex fault landscape, roboticists need adequate tools to monitor and address these issues. Robot middlewares (Elkady and Sobh, 2012) are one of these tools developed to abstract part of the complexity related to software design and hardware abstraction. However, in terms of fault tolerance, these robot middlewares (Elkady and Sobh, 2012; Brugali and Scandurra, 2009; Brugali and Shakhimardanov, 2010) usually address only single parts of the problem and most of the time the solution does not address MRS.

2.1 Individual Robots Fault Monitoring

Pettersson (Pettersson, 2005) classifies the monitoring methods into analytical, data-driven, and knowledge-based. The analytical methods (further classified as parameter estimation, parity relations, and observers) compare two analytically generated quantities obtained from different sets of variables and an analytical model. The data-driven methods derive fault detection directly from input data, usually by computing statistic measures. The most popular method of fault monitoring in robotics is to compare the sensors values with a pre-determined range of acceptable values (i.e. using thresholds). The knowledge-based approaches are designed to simulate the problem-solving skills of humans (e.g. artificial neural networks or expert systems), which combine both analytical and data-driven approaches to create a hybrid monitoring method.

Logging (Lotz et al., 2011) is another fault detection technique where data is collected in advance, to be analyzed later (off-line fault detection). During the normal runtime, all necessary data is collected and stored in some device. The disadvantage of this technique is that a huge amount of data can be generated. Usually logging needs another monitor to check if the device is not full and in need of clean-up actions. Logging can be used for both SRS and MRS.

2.2 Multiple Robots Fault Detection

Fault detection systems in MRS (Mendes and da Costa, 2010) have the distribution as a coefficient that increases the complexity of the process. The robots of an MRS must be able to cooperate and communicate with each other to achieve satisfactory performance and stability. A networked control system is a requirement to connect all robots through communication networks. Because of this complexity, these systems are subject to faults, performance deterioration, or operation interruption.

Kannan and Parker (Kannan and Parker, 2007) propose a metric for evaluation the effectiveness of fault-tolerance in MRS. Most existent metrics accounts for the system robustness based only on the redundancy of MRS. The ability of learning from faults and reasoning (e.g. replanning) are not accounted. The authors propose a new evaluation metric which is application-independent, and can be used to compare different fault detection approaches.

RoSHA (Multi-Robot Self-Healing Architecture) (Kirchner et al., 2014) is an architecture that offers self-healing capabilities for MRS. The architecture of the self-healing add-on should be resource efficient, to prevent indirect interferences. Scalability is another important requirement. The self-healing add-on should be independent from the size and distribution of an MRS. Beside these envisioned features of a self-healing architecture, humans should be still able to oversee and control the system. This work presents a very advanced proposal on how to handle the MRS dependability challenges. However, it does not detail how to address a possible solution and does not contain evidence that this proposal is already implemented.

Kaminka et al. (Kaminka et al., 2002) present an approach to monitor multi-agent systems by observing their actions by tracking the routine communication among these agents. The results show that the proposed approach has a monitoring performance comparable to a human expert. There is no evaluation on the computing performance overhead caused on each agent by the proposed monitoring. The authors state that the so called report-based monitoring requires modification on the robot's software plans, and it generates major network bandwidth usage. On the other hand, in this paper we show that our proposed method is not intrusive (i.e. it does require modifications in the robot software) and it does not have significant network bandwidth, memory, or CPU requirements.

DRUMS (Distributed Robot Monitoring System) (Monajjemi et al., 2014) is a tool for monitoring, fault detection and debugging in distributed robot systems. It integrates to the robot middleware used (e.g., ROS, player) and monitors interactions in user code, the middleware itself, the robot devices (e.g., sensors), network interfaces and more. Its output can be visualized with third-party tools by a human operator, or DRUMS can be used as a low-cost data collection, fault detection and diagnostics software layer.

3 PROPOSED ARCHITECTURE

This section describes the proposed Multi Robot Monitoring architecture and the tools related to it.

3.1 Used Robot Middleware

The ROS framework is designed to reduce the cost of software development for large-scale robots systems, providing the communication layer above the host operating system and the application. According to (Dudek and Jenkin, 2010) the ROS main characteristics are:

- Peer-to-peer communication to reduce traffic in the network. It uses publish/subscribe communication;

- Tools-based: micro kernel designed instead of monolithic kernel;
- Multi-lingual support;
- Thin: software development libraries with no dependencies on ROS;
- Free and open-source under BSD license;
- Organized in packages in order to build large systems;

ROS has a modular design that allows advanced communication functionalities, which could be extended to communicate with any kind of other tools. Moreover, the framework provides some tools for fault monitoring and diagnosis (Goebel, 2014; Foote, 2010). These tools are useful for development and monitoring one specific robot each time and not for the entire MRS. This solution addresses only part of the overall problem of runtime monitoring because they allow checking the status of one component/-module at time. The Diagnostics stack (Goebel, 2014; Foote, 2010) is the software responsible for analyzing and reporting the system state. It consists of development support for collecting, publishing, and visualizing monitoring information. This tool-chain is built around a standardized topic, named `/diagnostic` topic, where monitoring information are continuously published.

ROS also provides the `diagnostic_aggregator` ↪ package, which subscribes to the `/diagnostic` ↪ topic, reads the raw published data, reorganizes all information based on a set of pre-defined rules (YAML file), and publishes the generated result in the `/diagnostic_agg` topic. The `diagnostic.yaml` file defines groups to aggregate the information according with the type of data. For example, robots with more than one battery could aggregate all batteries statuses on a Battery group.

Another tool built-in on ROS is the `robot_monitor` tool. This is a GUI tool that displays all results published on the `/diagnostic_agg` topic in a hierarchical format. A double click on the selected information will open more details about the diagnostic. Different icons and colors make it easy to identify components in OK, ERROR or WARNING statuses.

3.2 Used IT Infrastructure Monitoring Tool

Nagios (Barth, 2008) is a platform for executing specific checks to monitor an entire system of networked

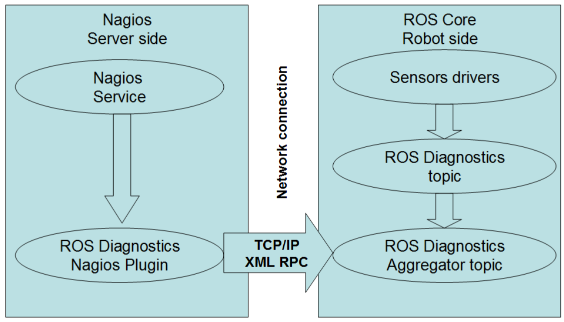

Figure 1: Software Architecture.

computers. It supports several different methods and protocols to access the remote computers, meanwhile being highly customizable such that it can monitor practically any kind of device information. For instance, the use of memory, free space on disks, CPU load, the number of processes, specific processes, and many other customized information. Nagios provides an easy web interface for graphical view of the entire system and simple navigation into the nodes, allowing searching for detailed monitoring information. Other resources that might also be useful in the context of robotics include SMS/email notifications and the display of time series dynamic charts of data collected from the hosts. Scalability is another characteristic of Nagios. Several non-central Nagios instances could send their results to a Nagios Central Server using the Nagios Service Check Acceptor.

Nagios has a flexible design that allows the development of extensions to communicate and to monitor almost any kind of system through a Nagios plugin (Nagios Enterprises LLC, 2017). The plugin is a small piece of software that must be developed following the Nagios plugin specification, in order to support the Nagios API. Plugins used for host and service checks are separate and independent programs that can also be used outside of Nagios.

3.3 Developed Architecture

The proposed software architecture, illustrated in Figure 1, connects Nagios through the developed ROS Diagnostics Nagios plugin (referred here as ROS plugin) directly with the ROS diagnostics aggregator topic on the remote robot. The ROS plugin connects to the ROS diagnostic aggregator node through ROS APIs and gets the requested information, printing the output on a standard output format required for the Nagios engine. All communications are executed using the XML-RPC protocol.

Nagios remotely connects to the robot and retrieves the required information. It does not require any additional software installed or running at the robot side. The only requirement is the diagnostic aggregator node, which is already present in most ROS-compatible robot platforms. On the Nagios server side, it needs the basic ROS installation to use the ROS protocols and standard diagnostic message formats.

The ROS plugin is a Python script developed to access the robot's ROS core node via XML-RPC, to remotely subscribe to the diagnostic aggregator topic of each monitored robot, and to parse the information in the Nagios output format. The proposed plugin is general in the sense that it is independent of the monitored device. It can parse information of any kind of robot with different number and types of devices.

The following example shows the robot's overall status, which is OK. It lists the name of topics which carry the status of different parts of the robot. The robot's overall status and its topics can have 3 possible statuses: OK, CRITICAL and WARNING. The overall status assumes the most severe status of all monitored topics.

```
$ ./ros-diagnostics_agg.py -H <host>
OK - OK Sensor(s) list:
/Camera, /Camera/Caml, /Laser,
/Laser/Laser1, /Laser/Laser2, /Motor,
/Motor/Motor1, /Motor/Motor2,
/Motor/Motor3, /Power,
/Power/Laptop Battery,
/Power/Robot Battery, /Temp,
/Temp/Sensor1, /Temp/Sensor2
```

The following example shows topics in different severity status. Figure 2 shows Nagios monitoring multiple robots with different statuses. The main table shows the statuses of two robots (#1 and #2 in Figure 2). Robot #1 has 6 checks and only the last one presents a warning state (Figure 2(c)), in yellow. Robot #2 has 9 checks, the 8th in critical state (Figure 2(a), in red) and a few other checks are in pending state (Figure 2(b), in grey) because the robot has been powered up recently. Robot #1 has a single check for all sensors (Figure 2(d)), while robot #2 has multiple checks for different sensors (laser, camera, battery). This scenario gives an example of two types of monitoring configurations: detailed or summarized.

```
CRITICAL - CRITICAL sensor(s) list:
/Camera, /Camera/Caml
WARNING sensor(s) list:
/Power, /Power/Laptop
OK sensor(s) list:
/Laser, /Laser/Laser1, /Laser/Laser2,
/Motor, /Motor/Motor1, /Motor/Motor2,
/Motor/Motor3, /Power,
/Power/Robot Battery,
/Temp, /Temp/Sensor1,
/Temp/Sensor2
```

The plugin also has the ability to monitor only specific sensors' status, instead of monitoring all robot's statuses. For example, the plugin syntax allows the monitoring of only battery statuses:

```
$ ./ros-diagnostics_agg.py -H <host> -
    ↪ N battery
OK - OK Sensor(s) list:
/Power, /Power/Laptop Battery,
/Power/Robot Battery
```

In this case, all other sensors not containing battery in the name are ignored by the plugin. The name parameter also allows more configuration flexibility on Nagios. For example, it allows monitoring of the Motor status every 5 minutes, and the temperature sensor every 30 seconds.

An important characteristic of this architecture is the fact that the monitor system is completely independent of the robot application, meaning that if the monitor server stops, only the monitor system will cease. The robotic system will carry on working as if nothing happened.

4 EXPERIMENTS

Two types of experiments are performed to evaluate the proposed architecture: a scalability experiment with up to 100 heterogeneous virtual robots, and an experiment with one real robot.

4.1 Server Scalability Experiment

Up to 100 heterogeneous virtual robots were executed at the same time to test the scalability of the monitoring server. The rest of this section details the virtual robot setup and the monitoring server setup.

Figure 3 illustrates the architecture of the scalability experiment. The Database server in the left side is not a solution requirement and was created only to collect performance data (e.g. cpu load, memory usage and network bandwidth) from the virtual robots during the experiment. Nagios server is running and the proposed ROS plugin is installed on the server side, without any change to the virtual robots' software. All computers (servers and robots) are on the same network, or equivalent via VPN. Details of this setup are presented in the next sections.

4.1.1 The Virtual Robot Setup

The virtual robot is a Python application, running on a Virtual Machine (VM), developed to generate diagnostic data typically generated by robots compliant with ROS diagnostics. The python application reads

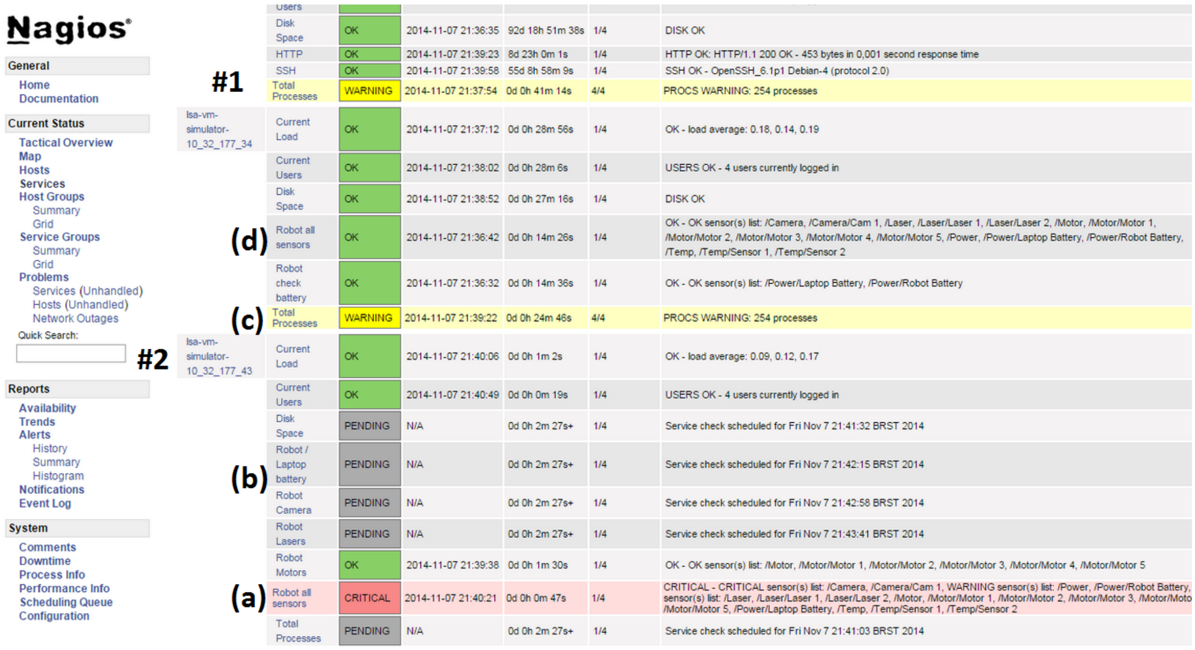

Figure 2: Nagios monitoring two robots with the proposed plugin.

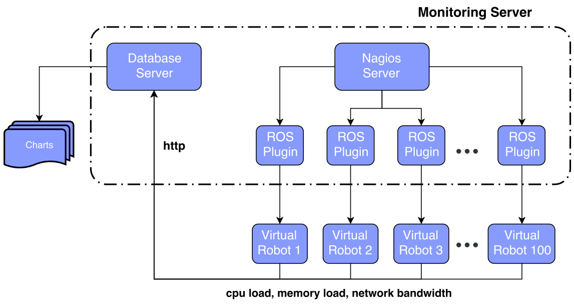

Figure 3: Schematic view of the server scalability experiment.

a set of configurations and, based on these configurations, it publishes data on the ROS diagnostics topic. The configuration defines the total number of sensors to be simulated and the number of sensors in warning and error states. As such, each virtual robot can simulate different numbers of monitored devices, characterizing an heterogeneous MRS.

All virtual robot diagnostic information is combined in a diagnostic aggregator node, which defines rules to parse the raw diagnostic information and categorize it into a more readable and meaningful way, on the `/diagnostics_agg` topic.

Figure 4 illustrates the RQT robot monitor, capturing the diagnostic information generated by the developed Python application. This figure shows a list of the monitored devices and their statuses. At left it shows the detailed information of the selected device.

The virtual robot is running on a virtual machine

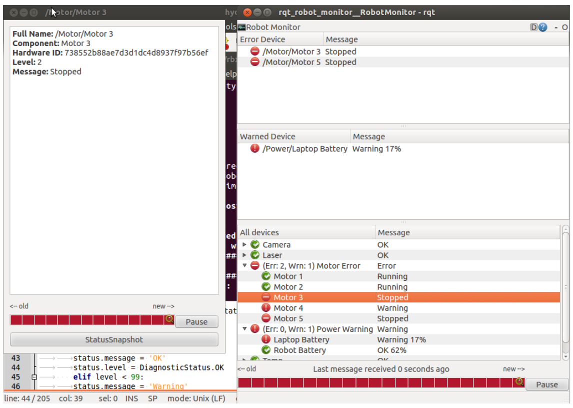

Figure 4: RQT screenshot of the simulator running on a virtual machine.

with 256 megabytes of RAM, and 1 processor running Ubuntu 12.04 and ROS Hydro. When a new instance of the virtual robots' VM is started up, it automatically sends its IP address to the Nagios server, to be included into the monitoring process. This script is only used in the experiment to ease the management of 100 virtual robots. When using real robots, no additional setup is required at the robots' side.

A status script was created to collect performance data during runtime and to send this information to the database server. This bash script runs on the guest OS and gets CPU usage from the `/proc` filesystem, the memory usage information from the "free" Unix command output, and calculates the bandwidth transmitted from `/sys/class/net` every minute.

4.1.2 Monitoring Server

The Nagios monitoring server is running on a virtual machine, created with 2048 megabytes of RAM and 2 processors running Ubuntu 13.10. It runs the Nagios server, a MySQL database server, an Apache HTTP server configured with PHP module enabled, and the proposed ROS plug-in used to collect ROS diagnostic information from the remote robots.

The database server is also used to collect all robot's performance data, gathered during the experiments presented in Section 5. As mentioned before, each robot periodically extracts its own CPU load, memory load and network bandwidth, and saves this information into the database server located at the monitoring server. This specific database is not required by the proposed solution. This is only used to ease the data capture of 100 simulated robots during hours of execution.

4.2 Experiment with Real Robot

The experiment with a real robot uses a Kobuki-based Turtlebot[1] mobile base, equipped with a Kinect depth sensor to avoid obstacles. One notebook with a Core i5 processor, 8GB of RAM memory, Ubuntu 12.04, and ROS Hydro, is used for running the application. The robot is programmed to perform autonomous navigation with collision avoidance, while diagnostic data is captured periodically.

The robot runs ROS' `kobuki_node`[2] package to access and control the mobile base, the `freenect_stack`[3] package to access the Kinect, and ROS' `move_base`[4] autonomous navigation stack (Goebel, 2014). The `kobuki_node` locally produces diagnostic information from the mobile base in real-time.

5 RESULTS

5.1 Server Scalability

This experiment evaluates the scalability of the monitoring server as the number of monitored virtual robots increases up to 100. Each virtual robot requires an average of 10 checks, as illustrated in Figure 2. The monitoring server and the virtual robot configurations are described in Section 4.1.

[1]http://kobuki.yujinrobot.com/about2/

[2]http://wiki.ros.org/kobuki_node

[3]http://wiki.ros.org/freenect_stack

[4]http://wiki.ros.org/move_base

Figure 5 in the appendix shows the monitoring servers performance while the number of virtual robots increases from 1 to 30, 60, and 100 instances. The evaluated performance parameters are CPU load, memory load, and network bandwidth. These parameters are collected every 5 minutes during 100 minutes for each configuration. For each of the 3 parameters, their mean (or average), median, and standard deviations (error bars) are presented in the following 3 charts.

These results show that Nagios, although overloaded with the presented VM configuration, can still monitor up to 100 robots. It is reported that Nagios can monitor thousands of computers (Barth, 2008), when a normal fully-configured server is used instead of this VM. If we assume one computer per robot, it means that thousand robots could be monitored.

5.2 Virtual Robot Performance Experiment

This experiment collects performance data at the robot side, in this case, at the virtual robot's VM. Performance data (CPU load, memory load, network bandwidth) was collected during 60 hours with different monitoring frequencies (no monitoring, every 5 minutes, and every 1 minute). The observed results are illustrated in Figure 6 in the appendix, where once again the mean, median, and standard deviations as error bars are presented in each chart.

These results show that the monitoring process has a small impact on the monitored VMs, even if we considered the minimal resources allocated for each VM, as described in Section 4.1. The network bandwidth shows an increasing pattern, however the chart's unit is kilobytes per minute, which is a very small amount of data.

5.3 Real Robot Experiment

This experiment evaluates the impact of the monitoring system on a real robot, running a common mobile robot software application for autonomous navigation. The robot's hardware and software configurations are described in Section 4.2.

Table 1 shows the performance data (CPU load, memory load, network bandwidth), collected during 30 minutes of navigation. First, data is collected when the monitoring system is off, and then the same navigation task is repeated with the monitoring system on. As mentioned before, no specific configuration or additional software is required on the robot to enable the proposed monitoring system. The results confirm the efficiency of the proposed method at the robot side.

Table 1: CPU load, memory load and network bandwidth at the real robot with the monitoring on (every 5 minutes) and off.

Item	Monitor Status	Mean	Median	Standard Deviation
CPU Load	Off	133.05	132.00	26.45
	On	135.75	129.00	43.30
	% of change	2.03	-2.27	63.71
Memory Load	Off	30.23	30.00	0.42
	On	30.81	31.00	0.39
	% of change	1.92	3.33	-7.60
Network BW (kB/s)	Off	0.19	0.00	0.71
	On	0.21	0.00	0.73
	% of change	7.58	N/A	2.52

6 CONCLUSIONS

This paper presented a lightweight and easy to configure monitoring infrastructure, to monitor the statuses of a large number of different robots during runtime. The proposed approach integrates consolidated tools for IT monitoring (Nagios) and robotics (ROS), which proved to be very effective and efficient for robotics.

In terms of usability, the proposed approach requires no modification or additional software on the robot side, other than the robotic framework. On the server side, the proposed ROS plug-in must be installed and the server must be able to access the robots via their IP addresses.

Experimental results show that it is possible to monitor 100 robots with a minimally configured Nagios Server, with the proposed ROS plug-in. The results also show that the monitoring impact on real robots is very small or negligible compared to the resources required to perform a usual autonomous navigation task.

As future work, we intend to use the proposed approach as a supervisory system, to monitor and log events of one or multiple industrial robots.

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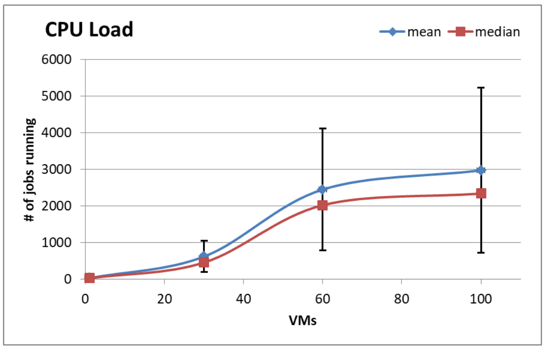
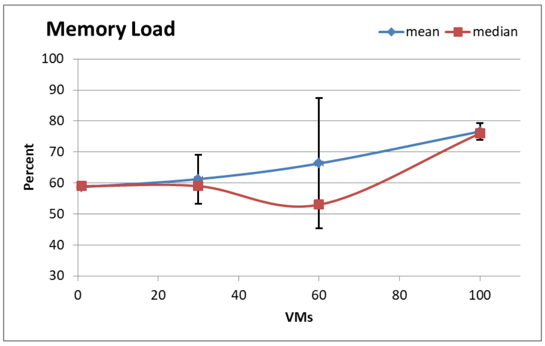
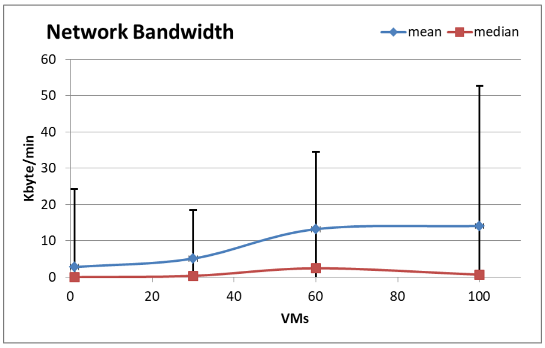
APPENDIX



(a)

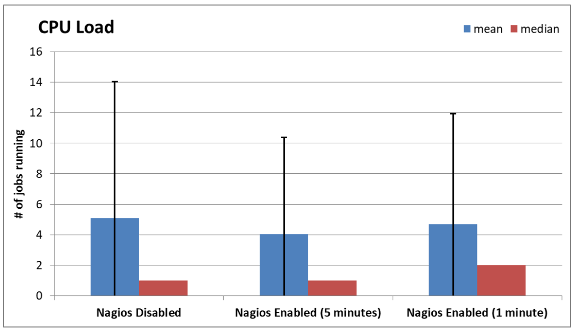


(b)

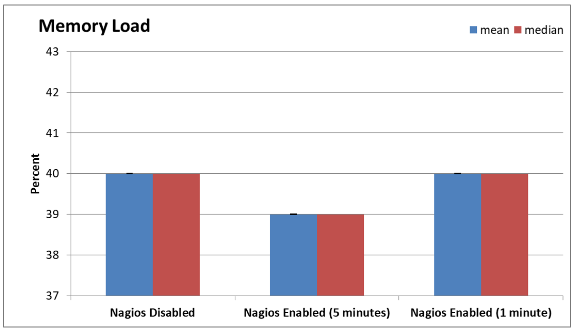


(c)

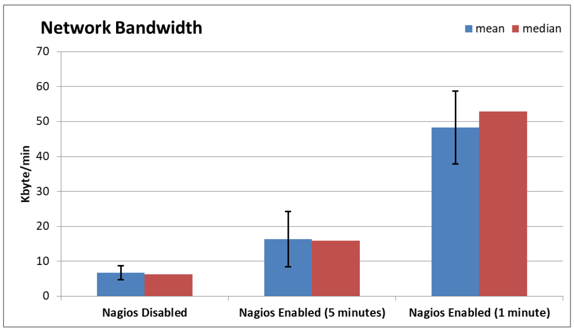
Figure 5: CPU Load (a), memory load (b) and network bandwidth (c) used at the monitoring server as the number of virtual robots increases.



(a)



(b)



(c)

Figure 6: CPU Load (a), memory load (b) and network bandwidth (c) used at the monitoring server as the monitoring interval decreases.