Semi–autonomous Shared Control for Redundant Forwarder Cranes

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Abstract

Semi–autonomous operation with *shared control* between the human operator and an autonomous control system has been developed and examined for a forwarder crane. *Shared control* gives the operator and the autonomous control system simultaneous control over the same task. It also enables smooth transitions between manual and autonomous operation. Operators with professional experience of forwarder crane control as well as inexperienced operators have been engaged in experiments where performance was measured. The experiments were conducted on a forwarder crane of reduced size at Smart Crane Lab, Umeå University. Three levels of automation were evaluated: pure manual operation, semi–autonomous operation with *traded control* and semi–autonomous operation with *shared control*. The semi–autonomous operation were examined along with two methods for manual operation: conventional joint control and boom–tip control.

The time–efficiency of log loading as well as smoothness of transitions between autonomous and manual operation were examined. The experiments show that with the aid of *shared control* the performance of the inexperienced operators increases with a factor two as compared to manual joint control. The performance of the professional operators decreases somewhat with *shared control* as compared to manual joint control. With *shared control* both professional and inexperienced operators experience a reduction in workload. Smoothness of transitions were found satisfactory.

Contents

1 Introduction

In final felling and thinning the most common machine system today consist of one harvester and one forwarder. The harvester fells, delimbs and bucks the trees into logs, thereafter a forwarder pick up the logs and loads them into its load bunk for transportation to the roadside. At the roadside the logs are loaded on a lumber car for further transportation to a sawmill or a pulp factory. Both the harvester and the forwarder is equipped with a hydraulically actuated crane. The harvester fells, delimbs and bucks with a harvester head attached to the boom–tip and the forwarder load logs with a grapple attached to the boom-tip. Today both the harvester crane and the forwarder crane are completely manually controlled by a human operator, but the forest industry has a long term goal to introduce automation in these machines. Research at Umeå University has shown that accurate, reliable, fast and stable autonomous control of a hydraulically actuated forwarder crane is feasible, given that the crane is equipped with robust sensors at each joint [20, 18, 17]. Although for a completely automated forwarder crane without the need of supervision from an operator there are still major challenges to solve. Automation of challenging tasks such as locate and determine orientation of a log or a pile of logs, as well as pick up the logs with the grapple require solutions that utilizes vision and human intelligence.

(a) Valmet 911.4 harvester

(b) Valmet 840.4 forwarder

Figure 1: The most common machine system today includes a harvester and a forwarder.

The next natural step is to introduce semi–autonomous operation of the crane. This means that some tasks are automated while the operator manually perform the other tasks. The harvester head already has automated delimbing and bucking tasks, though the harvester crane still is completely manually controlled. Skogforsk [7] have made a pilot study [12] in a simulator environment with automated tasks for the harvester crane. The study shows a decreased overall workload for the operator. For the inexperienced operator the productivity was increased with automated tasks. The inexperienced operators were only 20% slower than a professional operator with the automated functions enabled. Without automated functions the inexperienced operators only achieved 25% of the productivity level set by the professional operator. Simulator experiments at Skogforsk with boom–tip control of a forwarder crane [15] has shown positive results concerning faster learning, higher performance and less workload for the operator. By introducing automated tasks also for the forwarder, the workload may further decrease, the learning may be even faster and thereby the productivity is expected to increased.

It remains unclear, however, how the operator should interact with the automated tasks, especially in the transitions between manual and autonomous operation but also during the autonomous task. To allow the human operator to interact with the control system it requires that they have simultaneous control of all task parameters. This is called *shared control*. As a result of *shared control* the operator should be able to smoothly interact, take over and return control to the control system without interrupting the autonomous task. In this way the operator can manually avoid unexpected obstacles during autonomous tasks and it is also possible with smooth transitions between manual and autonomous operation. The transitions should occur without vibrations and slowdowns of the crane motion. Vibrations in transitions and delays due to slowdowns are annoying for the operator and probably results in that the operator does not use the automated tasks.

The work in [16] proposes a *shared control* architecture where the crane is controlled by a boom–tip velocity reference. The crane control is then shared between a human operator and an autonomous control system by merging a velocity reference from the human operator with a velocity reference from the autonomous control system. This work further develop and implement this *shared control* architecture for a real forwarder crane at the Smart Crane Lab [8] at Umeå University. The crane at the Smart Crane Lab is shown in figure 2, it is a forwarder crane of reduced size with a maximum reach slightly above 4.5 meters. Normal sized forwarder cranes typically has a maximum reach between 7 and 10 meters. The *shared control* approach is implemented for both conventional joint control and boom–tip control [19]. Experiments are then performed with professional operators as well as completely inexperienced operators. The experiments examine performance in log loading for both conventional joint control and boom–tip control along with three levels of automation: pure manual operation, semi-autonomous operation with *traded control* and semi-autonomous operation with *shared control*.

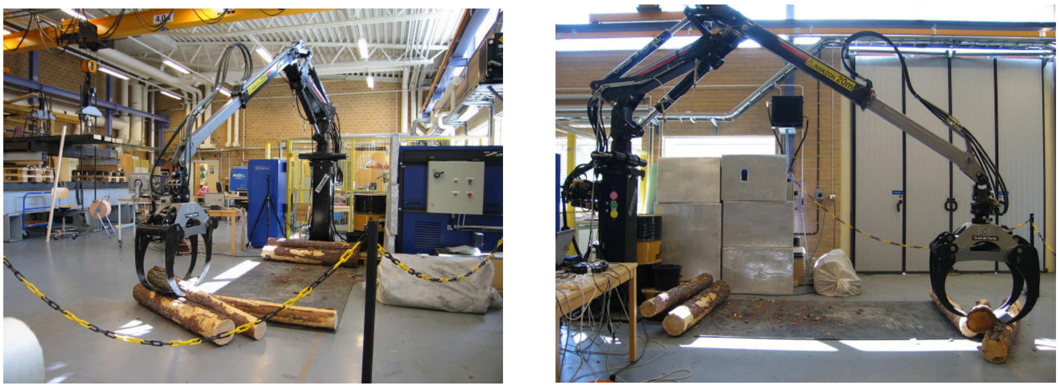


Figure 2: The forwarder crane of reduced size at Smart Crane Lab.

1.1 Purpose

The purpose of this project is to

- evaluate *shared control* methods for forwarder crane operation.
- improve and develop new methods for *shared control* and man-machine interaction.
- perform realistic experiments with shared control and man–machine interaction in simulator or a real machine. This experiments should investigate the necessity of semi-autonomous motions with *shared control* for both professional operators and inexperienced operators.

1.2 Objectives

The project should result in

- a realizable method for semi–autonomous motions with *shared control* for a hydraulically actuated forwarder crane.

- experimental results from a study of semi–autonomous motions with *shared control* for a hydraulically actuated forwarder crane.

1.3 Participants

Short description of companies and organizations related to this project.

IFOR With IFOR as a base performs Umeå University, Skogforsk [7] and SLU [9] research and development in collaboration with the industry. IFOR is acronym for the Swedish name "Intelligenta Fordon Off-Road" (in English "Intelligent Off-Road Vehicles") [2].

Umeå University At Umeå University Faculty of science and technology there is research that includes robotics, control systems and visual interactive simulation [10].

Komatsu Forest Machine manufacturer that develop Valmet forest machines [3].

Oryx Simulations Develop training simulators for Valmet forest machines and other heavy machines. The simulated forwarder in the virtual environment make use of 3D-models used in the Oryx simulators [5].

Algoryx Simulations The multi-physics engine AgX from Algoryx Simulations [1] takes care of the real time physics for the virtual environment used for prototyping.

1.4 Outline

A basic introduction to motion control of individual joints are given in section 2.2 while section 2.3 deals with motion control of the cranes boom–tip. To accomplish autonomous motions for a forwarder crane the geometrical construction as well as the geometrical configuration of the crane must be provided to the automation computer. The configuration is provided by sensors and the construction from engineering drawings. Section 2.1 deal with the geometrical construction of a typical forwarder crane.

The operator interface and the experimental set-up at Smart Crane Lab are described in section 3 and section 5 respectively. Together with section 4, section 5 also deal with the *shared control* approach implemented for the experiment, semi-autonomous operation etc. The procedure of the experiment is described in section 5.4, the results are presented in section 6 and the results are discussed in section 7.

2 Introducing theory

This section introduces the basics in autonomous control of a hydraulically actuated forwarder crane and then further refer to more detailed sources. It also describes the construction of a typical forwarder crane.

2.1 Kinematics of a forwarder crane

A crane consists of rigid bodies that are connected in joints and each joint is actuated with a hydraulic cylinder. A forwarder crane has typically four joints, three revolute joints and a prismatic joint, figure 3 shows this construction. A revolute joint, not shown in figure 3, rotates the crane around the crane base. This is the slewing joint which is denoted as θ_1. The other two revolute joints, denoted as θ_2 and θ_3, controls the inner and outer boom. The outer boom has a telescopic construction, this is the prismatic joint denoted as d.

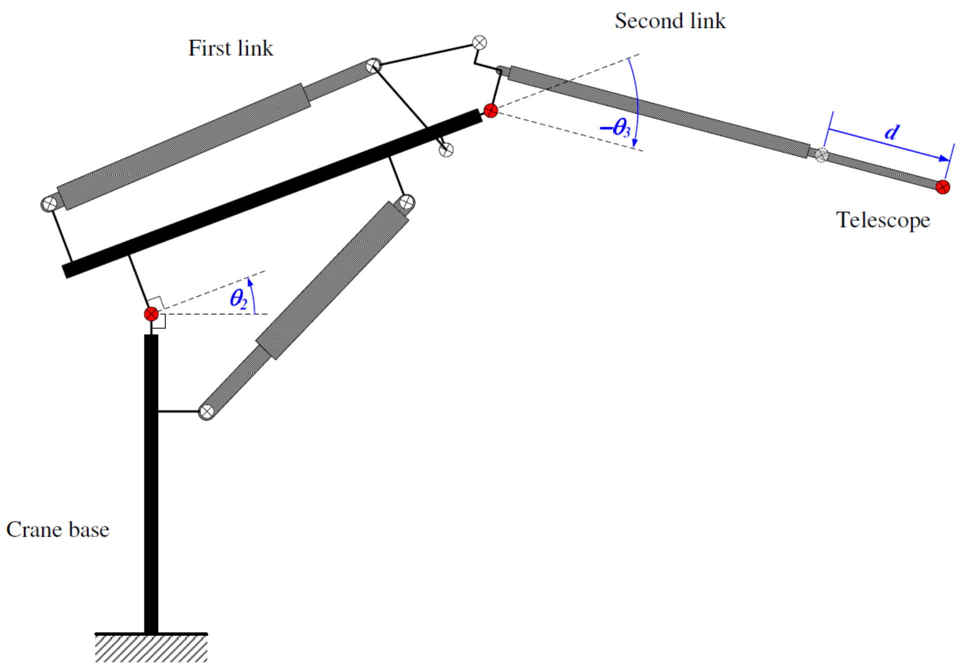
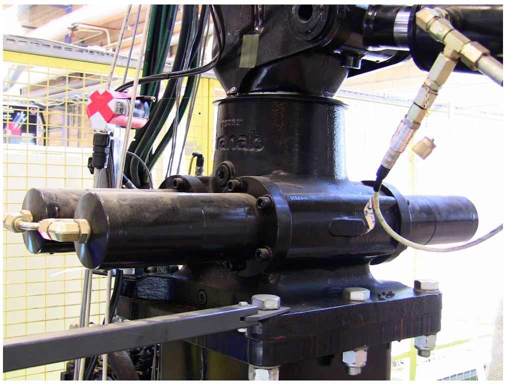


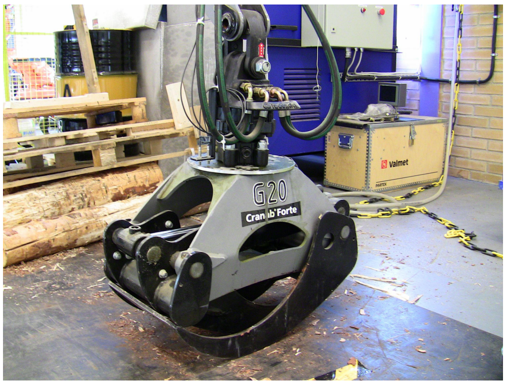
Figure 3: The construction of a typical forwarder crane. First and second link are also known as inner and outer boom. Figure from [22].

The slewing joint is actuated with a special type of hydraulic cylinder that is shown in figure 4a. A one–sided hydraulic cylinder attached to the crane base and the inner boom actuates θ_2, θ_3 is actuated by another cylinder attached to the inner and outer boom. The telescope is actuated with a hydraulic cylinder inside of the outer boom.

At the boom–tip typically a grapple is attached, as shown in figure 4b. The grapple and the crane is used for grabbing and lifting logs into the forwarders load bunk. The grapple is rotated, opened and closed by the operators commanded signals. Additionally the grapple has two unactuated degrees of freedom. These two joints are located at the attachment to the boom–tip and let grapple rotate around the attachment axis and its orthogonal axis.



(a) Slewing cylinder.



(b) Grapple.

Figure 4: The special type of hydraulic cylinder for the slewing and the grapple attached at the boom–tip of the crane at Smart Crane Lab.

2.1.1 Redundancy

The kinematic configuration of the crane is sufficient for operating in three dimensions. However, the prismatic joint introduce a redundant degree of freedom. This means that there exists an infinite number of joint configurations that will correspond to the same boom–tip position. In motion planning redundancy can be used to optimize the cylinder usage during an autonomous boom–tip motion. For example, the simplest optimization criteria is achieved by not moving each cylinder more than necessary, i.e. the work is spread out on all cylinders. By introducing a weight for each cylinder its kinetic energy is restricted, i.e. its motion is minimized by reducing the velocity. By properly selecting a weight for each cylinder the conceptual fuel consumption is diminished by avoiding motions of the heaviest links. For more information on redundancy, see [13, 14].

2.2 Motion control of individual joints

The crane control system ideally requires continuous information about the crane's geometry. Therefore, a crane must be equipped with position sensors at each joint. Sensors at the revolute joints gives an angular measurement while the telescopic extension of the outer boom is measured in units of length. To keep the crane in a desired joint configuration the control system uses sensor measurements as feedback to control the hydraulic cylinders.

PID control is a well known technique which do not requires any physical and dynamical properties of the system and relies only on sensor feedback. From the sensor measurement the *PID control* algorithm computes a control signal for the actuator. In this case the hydraulic cylinder is the actuator while the sensor measurement is the measured angle or extension at the joint, hence the joint position is controlled. In the literature the desired system state is called *reference value* or *set point*. The control error is defined as the difference between the *set point* and the sensor measurement. The final actuator control signal is calculated as a weighted sum of the present control error, the integral of the control error and the derivative of the control error. Thereof the name *PID control*, where *P* stands for proportional, *I* for integral and *D* for derivative. Figure 5 shows the concept of *PID control*. For more detailed information, see [11, 14, 16].

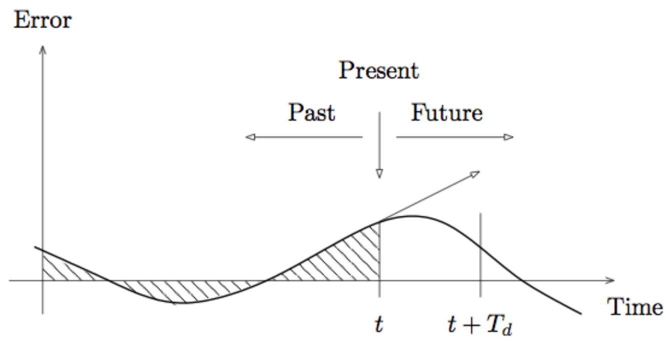


Figure 5: Illustration of *PID control*. The proportional part (P) consider the present control error, the integral part (I) consider the past of the control error and the derivative part (D) predicts future control error. Figure from [11].

In practical applications *PID control* is not sufficient for fast and accurate joint control, especially when considering a forestry crane. Hydraulic systems includes non-linear properties that are not trivial to deal with in developing of control algorithms. Variations in oil temperature may cause characteristic changes, further on oil leakage and friction introduces non-linearity in the system. Friction is a non-linear phenomena present in the mechanical linkage of the crane. Parameters of the mechanical linkage also drastically vary with external payload and the crane configuration. To further improve conventional *PID control* non–linear friction has to be identified and compensated. Besides, by pressure measurements from the hydraulic cylinders the acting force/torque generated by the hydraulic cylinder can be computed. By proper control of generated force/torque oscillations is expected to be counteracted more directly than with joint position control. Smoother position control can be achieved by simultaneous position and force/torque control combined in a two stage cascade control scheme. For more information on how to deal with non–linearities and damping of joint oscillations, see [20, 18, 17].

2.3 Motion control of the boom–tip

The design of autonomous boom–tip motions is considered as the high level control. It can then be left for the control system to translate the boom–tip motion into individual joint motions. This translation is referred to as inverse kinematics and utilizes the linear relationship between the boom–tip velocity and the joint velocities. From current joint positions and joint velocities resulting from the inverse kinematics new joint positions are calculated and then used as reference signal for the individual joint position controllers. As mentioned in section 2.1.1 a forwarder crane is typically redundant, which can be used for optimization of link usage. The optimization takes place in the translation from a boom–tip velocity to individual joint velocities. It is also possible to insert constraints on the individual joints, e.g. restriction in joint velocity and restriction in joint range. There are different methods to solve and optimize this problem, the interested reader is refereed to [13, 19, 15, 14, 21, 22, 16] for more information.

3 Operator interface

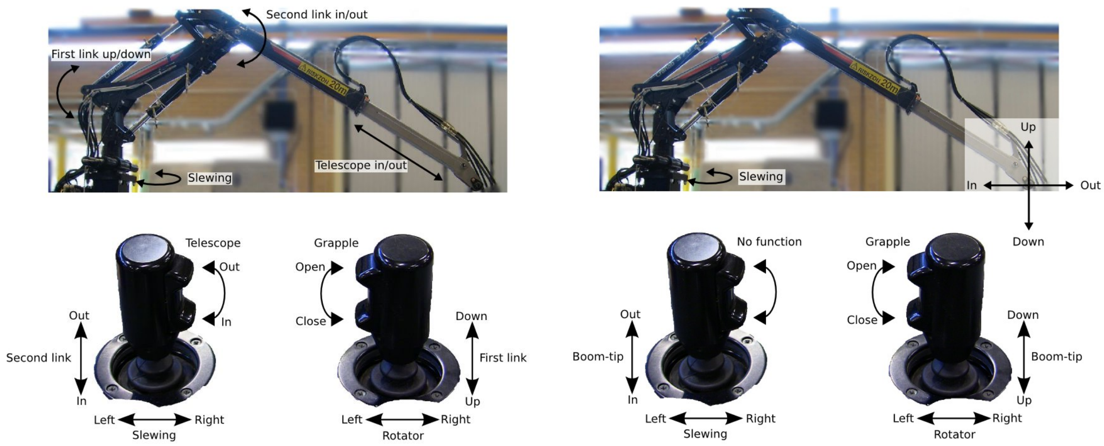
The operator interface and the operating methods available for the experimental set-up at Smart Crane Lab are described in this section. The experimental set-up is then further described in section 5. The crane is manually controlled from a chair that were found in Valmet forwarders a few years ago. The chair is supplied with two joysticks for manual control of the crane and several buttons with additional functionality. In autonomous mode the crane is controlled by a powerful real time computer.

(a) Chair. (b) The right joystick with buttons.

Figure 6: From this chair the crane at Smart Crane Lab is manually controlled.

3.1 Manual operating modes

For the experimental set-up two ways of manually operating the crane are available, conventional joint control and boom–tip control. In current commercial forwarders only joint control is available, boom–tip control requires robust sensor solutions and high performance computer control at each joint, which requires expensive equipment.



(a) Joint control. (b) Boom–tip control.

Figure 7: Manual control.

3.1.1 Conventional joint control

With joint control the operator individually control each hydraulic cylinder. To achieve a desired boom–tip motion it typically requires the operator to coordinate motions in several cylinders. In figure 7a it is shown how joystick movements corresponds to joint movements. This way of operating the crane is non–intuitive and claim years of training before the operator are productive enough. The power of joint control is that the operator can choose the exact crane configuration for a boom–tip position, which is very important in thinning. In thinning the forwarder is forced to operate in an environment where a great number of trees are left for further growing and it is very important not to damage those trees with the crane. With manual control of each individual joint it is easier to avoid hitting those trees.

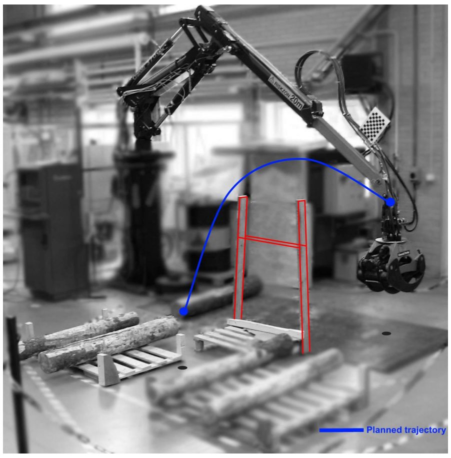
3.1.2 Boom–tip control

Instead of controlling each individual cylinder, the operator can directly control the boom–tip, a joystick movement then corresponds to a boom–tip motion. The signals from the joysticks are transformed into a velocity reference for the boom–tip. It is then calculated how the cylinders should move to achieve the boom–tip velocity reference. Figure 7b describe how joystick movements corresponds to boom–tip motions for the experimental set-up. As can be seen the operator has to think in a cylindrical coordinate system, i.e. the boom–tips extension, height and rotation around the crane base can be controlled by the operator. This is very similar to how a crane with parallel action is controlled, those cranes are typically found on harvesters [3]. An introduction with references to further reading on boom–tip control is given in section 2.3.

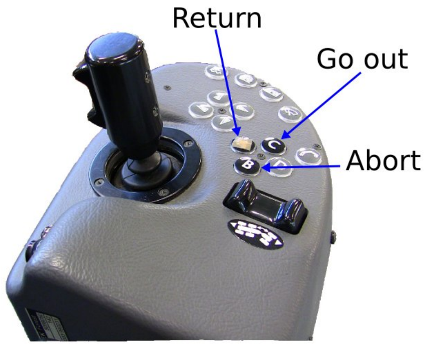
3.2 Semi-autonomous operation

With semi-autonomous operation the automation computer perform some of the tasks in the operators working cycle. For the experimental set-up two tasks are automated, *go out from the load bunk* and *go back to the load bunk*. The load bunk is the tray where logs are loaded on a real forwarder, in the experimental set-up the load bunk are marked with tape on the floor, the stakes that surrounds the load bunk on a real machine are marked with two symbolic stakes in the lab, see figure 16 and section 5 for a more complete description. The task *go out from the load bunk* moves the grapple from the load bunk, over the stakes and out to a specific point. Then it is assumed that the operator manually grab the logs. The task *go back to the load bunk* takes the grapple from outside the load bunk, by going over the stakes, back into the load bunk where the operator then manually proceeds by releasing the logs.

For the autonomous tasks described above a trajectory is planned from the boom–tips current position to a predefined final position. The automation computer then calculate a boom–tip velocity for moving along the trajectory. This boom–tip velocity is further translated into joint position references that should be achieved by the individual joint controllers. The autonomous tasks are controlled with buttons next to the right joystick. There is a button to start the task *go out from the load bunk*, another button to start the *go back to the load bunk* task and also a button to abort any ongoing autonomous task, see figure 8b. The experimental set-up has two modes for semi-autonomous operation, *traded control* and *shared control*. These two modes are described in the following sections.



(a) Semi–autonomous task.



(b) The buttons which control the semi–autonomous tasks.

Figure 8: Button A start an autonomous task to the load bunk, button C start an autonomous task out from the load bunk and button B abort any ongoing autonomous motion.

3.2.1 Traded control

In *traded control* mode the operator can not influence the autonomous task, the operator simply has to wait until the autonomous task is completed or manually abort it by pushing the abort button. The *traded control* mode typically introduce a stop of the crane motion at the transition between autonomous operation and manual operation. This stop is annoying for the operator because it break the rhythm and cause undesired pauses in the working cycle. Before the stop the crane motion is also smoothly deaccelerated, which prolongs the wait before the operator can take over for manual operation.

3.2.2 Shared control

In *shared control* mode the operator can interact with the autonomous tasks in a way that both the human operator and the autonomous control system simultaneously control the task parameters. This gives the operator a possibility to make adjustments to the automated motion without interrupting it. More importantly *shared control* is also a way to handle the transitions between autonomous and manual operation. With *shared control* the operator can smoothly take over the control when the automated task is nearly completed and in this way avoid the annoying pause that occur in *traded control*.

The *shared control* implementation consider velocity references for the boom–tip from both the autonomous system and the operator. These references are then weighted and merged together to a final boom–tip velocity reference which the control system should achieve. Figure 9 shows how the operator can interact with the autonomous task through *shared control*. When there is a contribution to the velocity reference from the operator the priority of the control system contribution is decreased. An operator contribution to the velocity reference will make the boom–tip deviate from the planned trajectory which the autonomous task should follow. If the operator stops contributing the boom–tip will smoothly go back to the planned trajectory again. If the operators contribution are large enough in a part near the end of a trajectory, the autonomous task is aborted. This gives a smooth transition between autonomous and manual operation. During an autonomous task the human operator contributes with a boom–tip velocity reference by using the joysticks in the same way as in manual operation of the crane, which is shown in figure 7. The *shared control* implementation is further described in section 4.2.2.

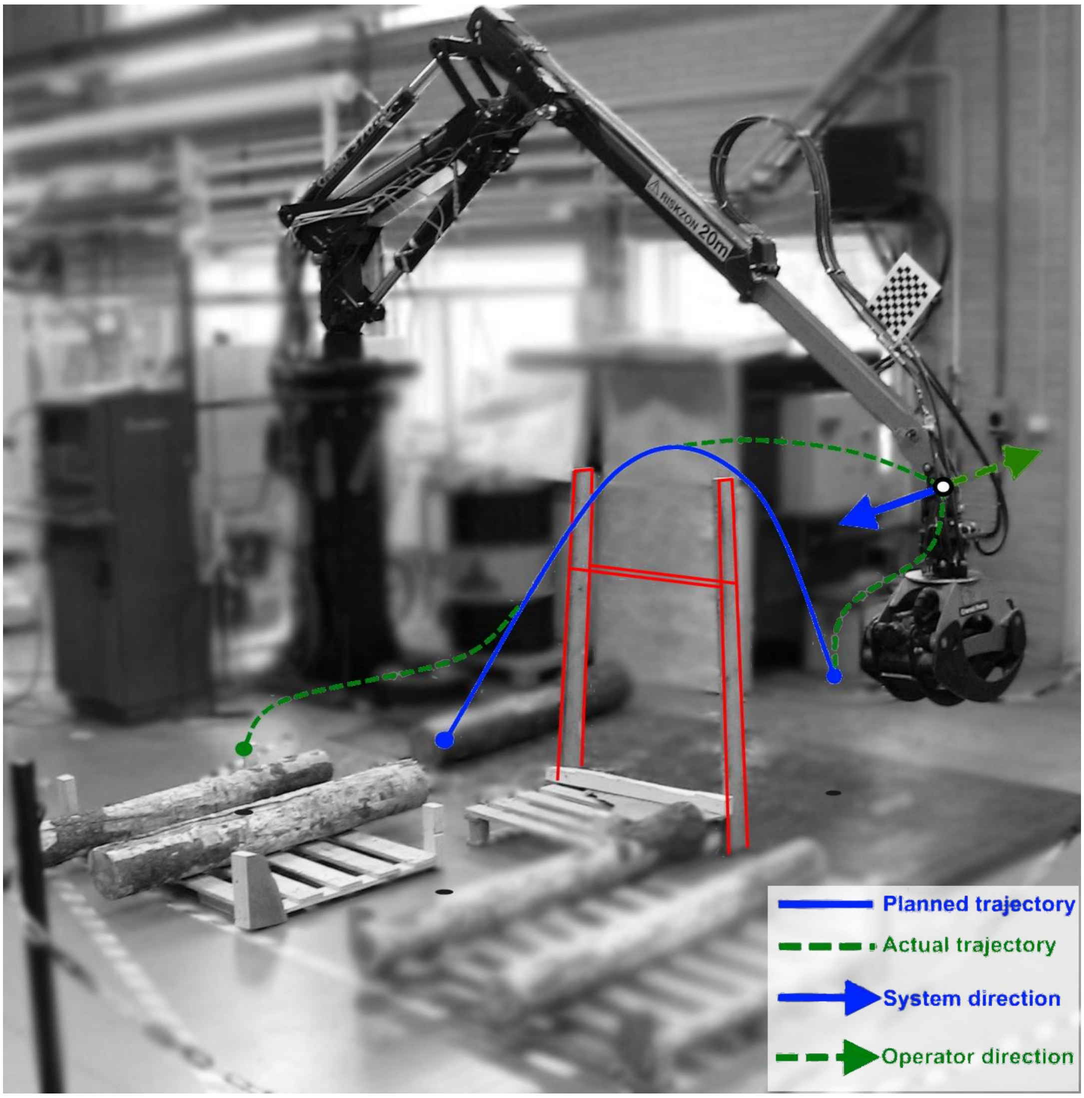


Figure 9: *Shared control* between the operator and the autonomous control system.

4 System description

This section describes the hardware for the experimental setup and gives a schematic overview of the software implementation for the experimental setup.

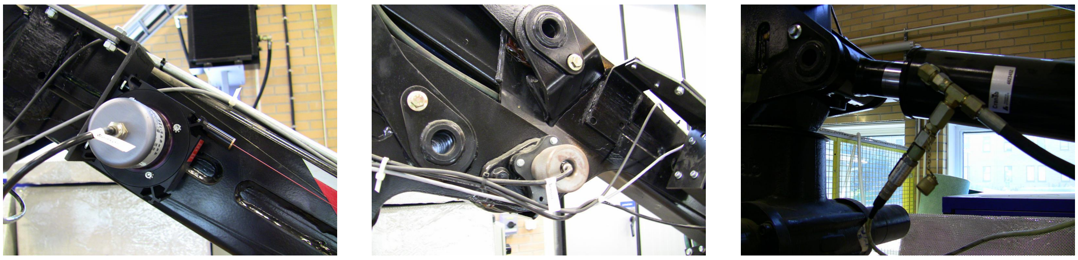
4.1 Hardware

Smart Crane Lab [8] at Umeå University is equipped with a forwarder crane of slightly reduced size, see figure 2. The crane has the same kinematics as described in section 2.1, i.e. it has three revolute joints and one prismatic joint. The three revolute joints corresponds to the kinematics of an elbow manipulator where the first joint control the slewing motions and the other two joints control the inner and outer boom respectively. With the prismatic joint it is possibility to adjust the length of the outer boom, which introduce a redundancy in the system. Redundancy is further described in section 2.1.1. When the prismatic joint is fully extended and the other joints are in a suitable configuration, the crane has a maximum reach slightly above 4.5 meters. Parameters for the crane are listed in table 1.

	Length [m]	Mass [kg]
Crane base	2.2	
Inner boom	1.4	357.5
Outer boom	1.82	117.5
Telescope	1.55*	75
Grapple		100

Table 1: Parameters for the crane. (*max extension)

The crane is supplied with different sensors. There are sensors that measure the pressure in the hydraulic cylinders and there are sensors that measure the angle/extension at the joints. The sensor measurements are used by a powerful real time `dSPACE` system called `MicroAutoBox (MABX)` [8] for autonomous control of the crane. The sensors are shown in figure 10.



(a) Telescope sensor. (b) Revolute joint sensor. (c) Pressure sensor.

Figure 10: Sensors for measuring the extension at the prismatic joint (telescope), the rotation in the revolute joints and pressure in the hydraulic cylinders.

The crane is manually operated from a chair, see figure 6a, identical to the chair in Valmet forwarders. The chair includes left and right joysticks with appertaining buttons. The joysticks and some of the buttons are connected to the `dSPACE` system which allows for both direct coupling of the joystick signals to the cylinder valves or computer control coupled to the joystick and button signals.

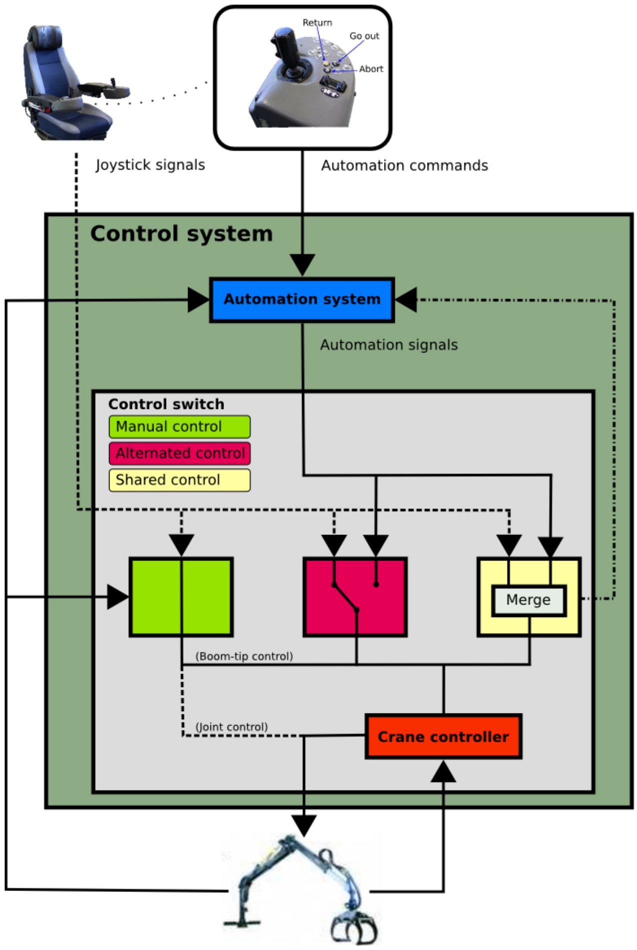


Figure 11: Schematic overview of the crane's control system.

4.2 Control system

The crane's control system is modelled in the `Matlab Simulink` environment [6], then `C`–code is generated from the model and thereafter loaded into the `dSPACE` system. For practical reasons generation of a trajectory and computations of trajectory tracking signals for autonomous motions are done on a separate laptop computer. The tracking signals are then sent to the `dSPACE` system with the `upd` network protocol. This is further described in section 4.2.3.

A simplified overview of the complete control system for the experimental setup is provided in figure 11. It shows how control signals from the operator and the automation system are combined and further sent to the crane controller. From reference angles and sensor measurements the crane controller control the position of each individual joint by actuating its hydraulic cylinder.

As described in section 3 there are two manual operating modes, joint control and boom–tip control, which are combined with three levels of automation, manual operation, *traded control* and *shared control* control. In manual joint control the control signals from the operators joysticks are directly coupled to the cylinder valves at the crane. Boom–tip control requires sensor measurements at each joint to determine reference signals for the crane controller who actuates the cylinders to achieve the desired boom–tip motion. Manual control is depicted with green in figure 11.

In *traded control* reference signals to the crane controller comes alternately from the human operator or the automation system. When an automated task is started the signals from the automation system are selected until the task is finished or aborted by the operator, otherwise the operators signals are selected. Thus there is no way for the operator, except from abort the task, to influence the automated task. *Traded control* is depicted with pink in figure 11. *Shared control* let the operator influence the autonomous motions. This is accomplished by merging the operators signals with the automation signals. Section 4.2.2 further describes the *shared control* implementation. In figure 11 shared control are depicted in cream white.

4.2.1 Pseudo joint control

The implemented shared control approach builds on merging of velocity references from the operator and the automation system. The fact that boom–tip control use velocity references makes it very suitable for the selected *shared control* approach. On the other hand, with manual joint control the joystick signals are directly coupled to the cylinder valves, hence no velocity reference for the boom–tip is given. This makes the selected *shared control* approach more complicated together with joint control. a work around called *pseudo joint control* that is more suitable together with the selected *shared control* approach was therefore developed and implemented.

Pseudo joint control translates the operators joystick signals into a velocity reference for the boom–tip. Boom–tip control is then used in a way that makes the crane responds as in joint control. In this way the selected *shared control* approach can be accomplished together with joint control as well. This is implemented with direct kinematics and inverse kinematics. Instead of a joystick signal that directly controls the cylinder valve, the joystick signal is translated into a joint velocity for the concerned joint. This joint velocity are then used in direct kinematics to calculate a velocity reference for the boom–tip. After the velocity reference are merged with the velocity reference from the automation system inverse kinematics is used to calculate velocities for each individual joint. These joint velocities are then further used to calculate extension and angular references to the crane controller.

In the inverse kinematics calculation parameters can be selected to restrict joint motions, see section 2.3. When there is only a velocity reference from the operator this parameters are selected in a way so that the crane behaves as in joint control. When there is only a velocity reference from the automation system the parameters are selected in a way that the revolute joints have equal weights and the prismatic joint has higher weight than the revolute joints. Hence the crane make more use of the telescope than the revolute joints. When there are velocity references from both the operator and the automation system the parameters are selected in a way that all joints can be moved, though the joints controlled by the operator have much higher priority than the other joints. Due to implementation issues *traded control* is also based on pseudo joint control.

The *pseudo joint control* implemented for the experimental setup suffer some artifacts. In total it is more bumpy than conventional joint control and in some crane configurations it starts to jitter. The performance of *pseudo joint control* can possibly be improved by more accurate tuning of parameters.

4.2.2 Autonomous tasks with shared control

For the experimental setup there are two automated tasks, *go out from the load bunk* and *go back to the load bunk* which are controlled with the buttons next to the operators right joystick, see figure 8b. These tasks takes the cranes boom–tip out of the load bunk and back into the load bunk. Basically the two tasks are made up of an initial generation of a trajectory from the boom–tips current position to the desired final position, then tracking of the trajectory begins and lasts until the final position is reached or the task is aborted. During the tracking part the automation system continuously provides the crane controller with a boom–tip velocity reference. The velocity reference are transformed into joint velocities and further into joint positions achieved by the crane controller.

In figure 12 the implemented *shared control* approach is illustrated. With *shared control* the operator can influence the automated task, this is achieved by merging the operators boom–tip velocity reference with the velocity reference from the automation system. Velocity references from the operator is a function of joystick inputs, the velocity references from the automation system is a result of the tracking calculations.

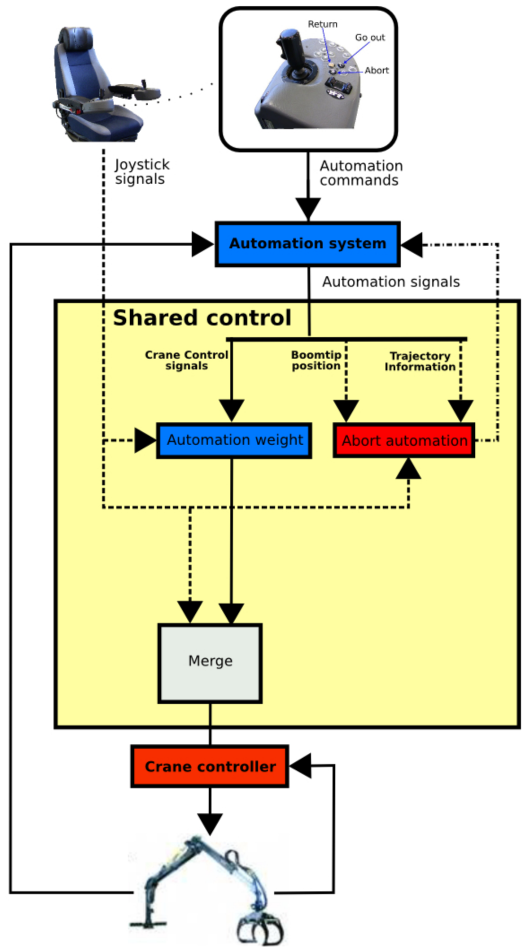


Figure 12: Detailed overview of the *shared control* software.

At each time–step it is assumed that the trajectory should be tracked with a specified speed. The boom–tip velocity is determined from this speed and a direction calculated with a tracking algorithm, which is described in detail in [16]. The basics of the algorithm are illustrated in figure 13, where point $\mathbf{c}$ is the point on the trajectory that is closest to the boom–tip, $\mathbf{c}'$ is the aiming point and $\mathbf{p}$ is the current boom–tip position. The velocity reference from the automation system, $\mathbf{v}_p$, is determined from the specified speed and the direction of the vector $\mathbf{c}' - \mathbf{p}$. The distance between $\mathbf{c}$ and $\mathbf{c}'$ depends on the boom–tip deviation from the trajectory, i.e. the distance between $\mathbf{c}$ and $\mathbf{p}$, an increased deviation corresponds to an increased distance between $\mathbf{c}$ and $\mathbf{c}'$. Deviations from the trajectory occur when the operator influence the task, so this change in distance between $\mathbf{c}$ and $\mathbf{c}'$ will result in a smooth return to the trajectory when the operator stops to influence the task. The vector $\mathbf{v}_{operator}$ is the velocity reference from the operator and $\mathbf{v}$ is the final result after $\mathbf{v}_p$ and $\mathbf{v}_{operator}$ are merged together.

Before the velocity references are merged a weight between 0 and 1 is applied on the automation system reference. This weight depends on the joystick signals from the operator, increased joystick signals results in a decreased weight. That is when the operator does not move the joysticks the automation system weight is 1. When the operator has moved the joysticks over a certain level the automation system weight is 0 and in between there is a smooth change. In this way the operators take over and return of control becomes smooth. The weight is illustrated as a blue rectangle inside of the *shared control* rectangle in figure 12.

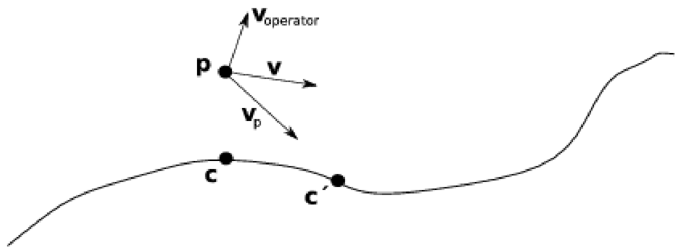


Figure 13: Trajectory tracking with *shared control*.

If the boom–tip is closer than a threshold distance from the end of the automated trajectory, the autonomous task can be aborted by large enough joystick signals from the operator. That is, in the end of a trajectory the operator can influence where the tracking of the trajectory ends and smoothly take over to. When the distance between the boom–tip and the end of the trajectory are above the threshold, the operators influence does not abort the autonomous task. The autonomous task will smoothly return the boom–tip to the trajectory once the operator gives no signal. Finally the merging of the velocity references could be a simple sum or an average. Aborting of the autonomous task with *shared control* is illustrated as a red rectangle inside of the *shared control* rectangle in figure 12

4.2.3 Trajectory generation and tracking from a separate computer

For practical reasons the planning and tracking of the trajectory are performed at a separate computer. When the operator press one of the automation buttons a trajectory is generated and then tracked. The generation is done once just after the button is pressed. However, the tracking part last until the end of the trajectory is reached. It is not strait forward to implement such a trajectory generation function in `Simulink`. Since a trajectory generation function and tracking computations already was implemented in C++ for the virtual environment, the existing implementation was selected. This requires that the trajectory generation and tracking is executed on a separate computer. Information is transferred between this computer and the `dSPACE` system with network communication.

To start with, information on when to start and when to stop an autonomous task must be sent between the two computers, that is when the operator starts a task by pushing a button or aborts a task by pushing the abort button. A task can also be aborted by *shared control*, which is considered in section 4.2.2. The start/stop communication is handled with the `tcp/ip` protocol. From the `dSPACE` system start/stop packages are sent to the other computer, which always answer with confirmation packages. The same procedure is applied when the information goes in the other direction. Figure 14 shows the communication packages.

For generation and tracking of the trajectory, the current boom–tip position must be available at that computer. Generation only needs the boom–tip position once, but the tracking part must have access to the boom–tip position at each time–step. Also a velocity reference has to be provided to the `dSPACE` system at each time step. This is solved with network communication by the `upd` protocol instead of `tcp/ip`. That is, at each time–step the boom–tip position is sent from the real–time computer to the the other computer, which in each time–step calculate and send back a velocity reference for the boom–tip. The cycle times at the two computers are not synchronized or even at the same frequency, but the frequencies are so high at both computers so it would not affect the practical experience.

8 bit	8 bit	64 bit	64 bit	64 bit
Message	**Info 1**	**Info 2**	**Info 3**	**Info 4**
Start task	Task type	Info 2	Info 3	Info 4
Stop task	Task type	0	0	0
Task started	Task type	Info 2	Info 3	Info 4
Task finished	Task type	Info 2	Info 3	Info 4
Task aborted	Task type	Info 2	Info 3	Info 4

Message	
Start task	0x01
Stop task	0x02
Task started	0x03
Task finished	0x04
Task aborted	0x05

Task type	
Go to position	0x01

Start task Go to position		**Position to reach**		
Start task	Go to position	position x	position y	position z

Task started Go to position		**Position to reach**		
Task started	Go to position	position x	position y	position z

Stop task Go to position		**Zeros**		
Stop task	Go to position	0	0	0

Task finished Go to position		**Position reached**		
Task finished	Go to position	position x	position y	position z

Task aborted Go to position		**Position reached**		
Task aborted	Go to position	position x	position y	position z

Figure 14: `tcp/ip` network communication packages.

5 Experimental set-up

The experiment environment, the experiment design, data logging as well as the test subjects are described in this section. It also introduce a virtual environment used for prototyping of algorithms.

5.1 Prototyping in a virtual environment

A first version of a simulator framework including virtual environment possibilities for control of mechanical systems is developed in [16]. The purpose of the framework is to provide an easy way to develop, prototype and evaluate high level control algorithms and man–machine interaction for mechanical systems. In collaboration with Algoryx Simulations [1] the simulator framework is provided with a virtual environment module based on the AgX physics engine and the 3D–graphics toolkit OpenSceneGraph [4]. The physics engine provides the virtual environment with real–time physics based on rigid multibody dynamics according to Newton–Euler's equations of motion. The complete framework is developed as a `C++` library, applications are developed as external stand alone applications that use the library code provided by the framework. The framework is further described in [16].

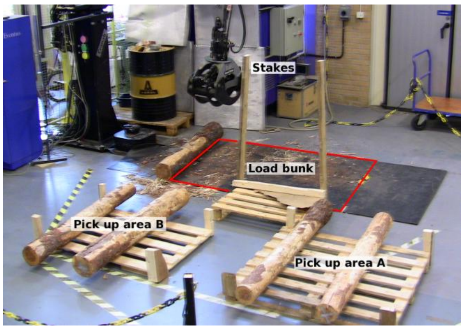
A virtual environment application with terrain, real forest stands, logs and a forwarder with semi–autonomous crane control is developed. The simulated forwarder includes joint sensors, PID controllers, motion planning, inverse kinematics, conventional joint control, boom–tip control, autonomous tasks and force feedback joysticks. Figure 15 shows the forwarder in the virtual environment. Before *shared control* has been implemented for the crane at Smart Crane Lab, *shared control* approaches has been implemented and briefly evaluated with the simulated forwarder.

(a) (b)

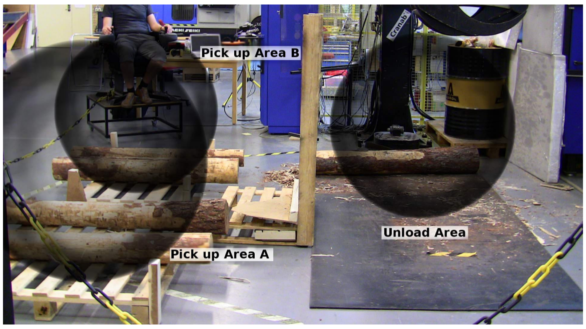
Figure 15: Experiments with *shared control* in the virtual environment.

5.2 Experiment environment

An environment inspired by the real forwarder and its working environment is arranged in the lab. An area that represent the machines load bunk is marked with tape on the floor while two symbolic stakes represent the right stakes of the machines load bunk. To the right of the stakes two areas are constructed from two box pallets, on each of the box pallets two logs are placed. The logs have a length of approximately 1.5 meters and a diameter between 0.15 and 0.20 meters. With this environment a simple loading scenario can be designed for experiments in the lab.



(a) Load bunk, stakes and the two areas where logs are picked up.



(b) The time spent by the boom–tip inside and between the spherical zones is logged.

Figure 16

5.3 Logging of data

Control signals and information about the operators activity is stored for later analysis. Time stamps are provided each time the boom–tip enter and leaves the load bunk and the two pick up areas. Figure 16b shows how the areas that determine the time stamps are defined by spheres with a radius of 0.7 meters. The leader of the experiment manually set time stamps when a log is grabbed and released. From the time stamps the amount of time while the boom–tip is moved between a pick up area and the load bunk as well as the amount of time spent inside the areas can be extracted. From this arrangement the operators working cycle is divided into four tasks, the amount of time spent between leaving the unload area and entering a pick up area is the subtask *go out from the load bunk*, the amount of time between entering and leaving a pick up area is the subtask *grab logs*, the amount of time between leaving a pick up area and entering the unload area is the subtask *go back to the load bunk* and the amount of time between entering and leaving the unload area is the subtask *release logs*.

During the whole scenario the positions and velocities are logged for the boom–tip and for each individual joint. The velocities are estimated from the joint position measurements. From this data the duration of the working cycle and its subtasks can be extracted together with velocities and positions for the boom–tip and individual joints.

5.4 Experiment design

A loading scenario similar to the loading task for a forwarder is considered in the lab environment, which is described in section 5. In the scenario the operator should load four logs into the load bunk. There are two logs with a length of approximately 1.5 meter and a diameter between 0.15 and 0.20 meters located at each pick up area. The logs should be loaded one by one in a pre–defined order. Figure 17 show the logs with numbers. The loading should start with log number one and end with number four. A loading task includes go out with the grapple to the log, grab the log with the grapple, go back to the load bunk and release the log. The grapple should go above the stakes during motions between the load bunk and the pick up areas. This loading task constitute one working cycle for the operator. In the scenario there are four logs that should be loaded one by one which results in four working cycles.

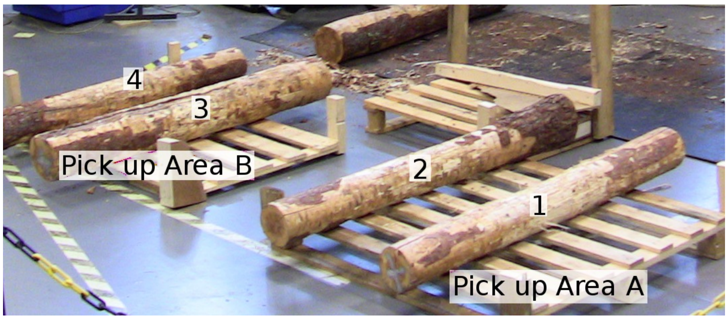


Figure 17: The logs should be loaded one by one from one to four.

5.4.1 Test series

Two control modes, *joint control* and *boom–tip control*, are combined with three levels of automation, *manual operation*, *traded control* and *shared control* which results in six different methods:

1. *manual joint control* – the operator manually loads the logs with conventional joint control as described in section 3.1.1.
2. *traded control together with manual joint control* – the operator use autonomous tasks alternated with manual joint control as described in section 3.2.1.
3. *shared control together with manual joint control* – the operator use autonomous tasks and manual joint control as described in section 3.2.2.
4. *manual boom–tip control* – the operator manually loads the logs with boom–tip control as described in section 3.1.2.
5. *traded control together with manual boom–tip control* – the operator use autonomous tasks alternated with manual boom–tip control as described in section 3.2.1.
6. *shared control together with manual boom–tip control* – the operator use autonomous tasks and manual boom–tip control as described in section 3.2.2.

The scenario described in section 5.4 makes up one test series, each method are tested in two test series. Totally one experiment includes twelve test series.

5.5 Test subjects and their preparation

Subject for the experiment are both professional operators and novice operators. The professional operators already mange conventional joint control impeccable. Boom–tip control is very similar to operating a crane with parallel action, in which the professional operators has experience from in operating a harvester (a crane with parallel action is very common on harvesters). Before the experiment the professional operators are given some time to be familiarized with boom–tip control and the interface to the autonomous tasks. The novice operators on the other hand will hardly manage the conventional joint control at the beginning, therefore a training session is designed for the novice operators.

5.5.1 Training session for novice operators

In order to prevent undesirable damage on the equipment due to difficulties with joint control, the novice operators go through a training session before the experiment starts. The training session lasts for approximately 1 hour and includes exercises in joint control. In the end of the session the novice operators are familiarized with grabbing logs with the grapple, boom–tip control and the interface to the autonomous tasks. The following exercises for joint control are included in the training session:

1. extend and withdraw the boom–tip as a strait line by using the two joints that control the inner and outer boom.
2. extend and withdraw the boom–tip as a strait line by using the three joints that control the inner boom, outer boom and the telescope.
3. keep the boom–tip in a strait line perpendicular to the lines in exercise one and two. All joints should be used.
4. with a grabbed log, move the crane forth and back over an obstacle in the vertical plane of the line in exercise three.
5. move the crane in a loading motion over an obstacle without restrictions. Also includes exercise on grabbing and releasing a log.

6 Results

The experiment has included five subjects, two professional operators and three novice operators. They have all done the experiment as described in section 5.4. A time study concerning the operators working cycle is done for each of the six control methods described in section 5.4.1. Section 6.1 present the result from this time study. Further, velocities and positions are logged for all the joints. From that the boom–tip position and velocity are calculated and logged. A vibration measurement for the boom–tip is computed separately for both a complete test series and in transitions between autonomous and manual operation. Results concerning boom–tip vibrations are presented in section 6.2.

After the experiment was fulfilled the subjects filled out a form concerning their experience of the experiment. The form contains questions where the subject should estimate different aspects of the experience on a scale from 1 to 10. Each question also includes a possibility for the operator do leave additional comments concerning the experience. Results from the forms are summarized in section 6.3.

6.1 Time study

The operators working cycle can be divided into four subtasks, *go out from the load bunk*, *grab logs*, *go back to the load bunk* and *release logs*. During an experiment the time for each subtask is measured as described in section 5.3. For each of the six control methods described in section 5.4.1 an average working cycle time is calculated as the sum of each subtask average for each individual operator. The subtask averages are calculated from subtask samples from the test series in each specific control method. Results from the time study are presented in figures 18, 19 and 20 on the following pages.

Figure 18 compares the average working cycle of professional operators and novice operators for each control method. With conventional joint control the inexperienced operators are almost 3.5 times slower than the professional operators. With manual boom–tip control the professional operators performs on the same level as with conventional joint control. The inexperienced operators are 1.7 times faster with manual boom–tip control than with conventional joint control and compared to the professional operators they are almost 2 times slower. When autonomous subtasks are considered the professional operator performance decrease compared to manual operation. With *traded control* the performance decrease by a factor 1.5. This is expected due to transition delays. With *shared control* the decrease is more marginal. The average *shared control* working cycle for professional operators was for boom–tip control 22.5 seconds and for joint control 25 seconds. This is compared to the average working cycle for manual operation that was 19 seconds for both joint control and boom–tip control.

The inexperienced operator performance increase for both *traded* and *shared control*. The best performance is achieved with boom–tip control together with *shared control*. Compared to manual joint control the inexperienced operators are here 2.2 times faster. Compared to the professional operators the inexperienced operators are 1.6 times slower. Figure 19 additionally includes the individual operators average working cycle and figure 20 further includes subtask averages for each individual operator.

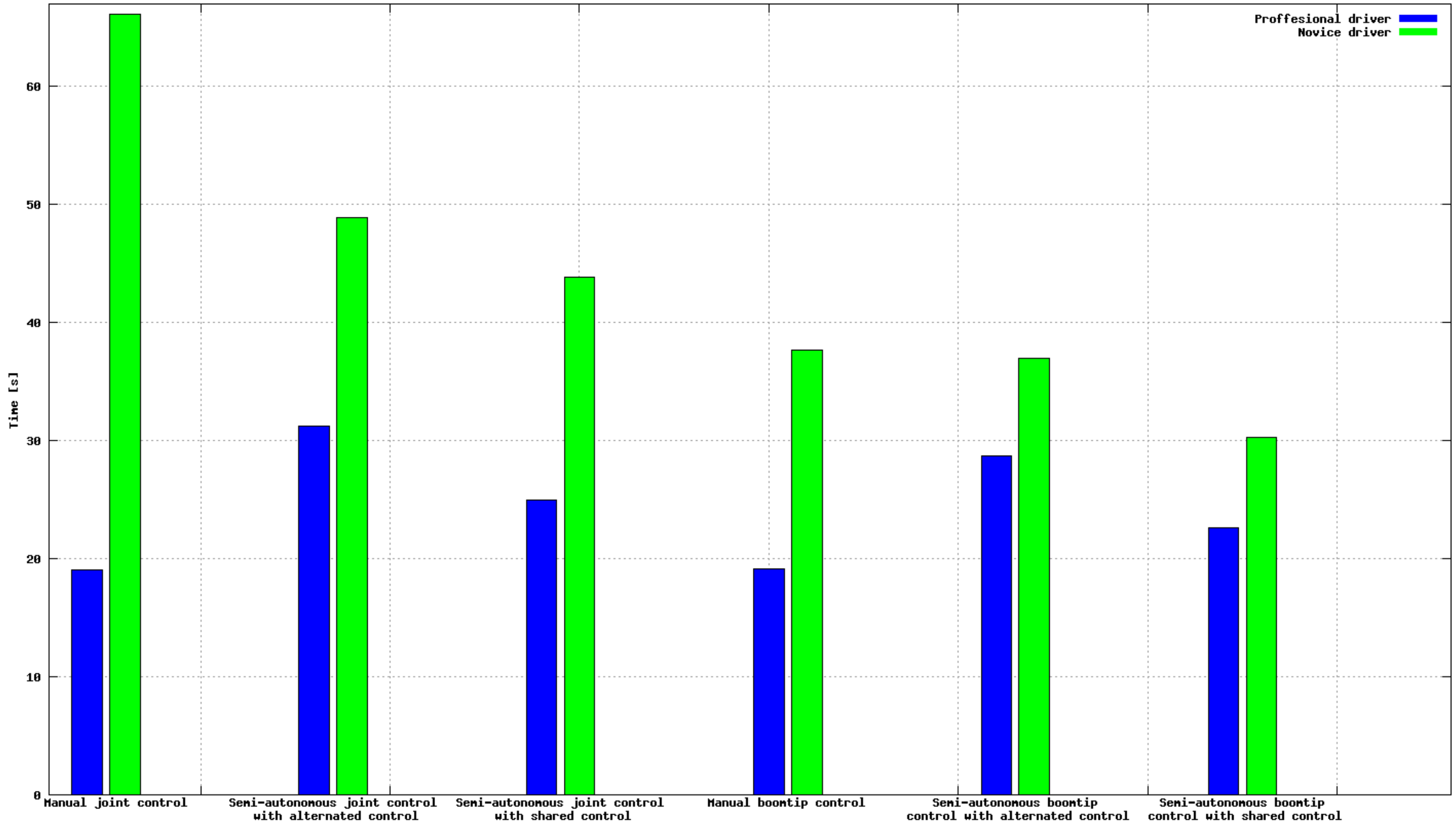


Figure 18: Work cycle average for professional and novice operators.

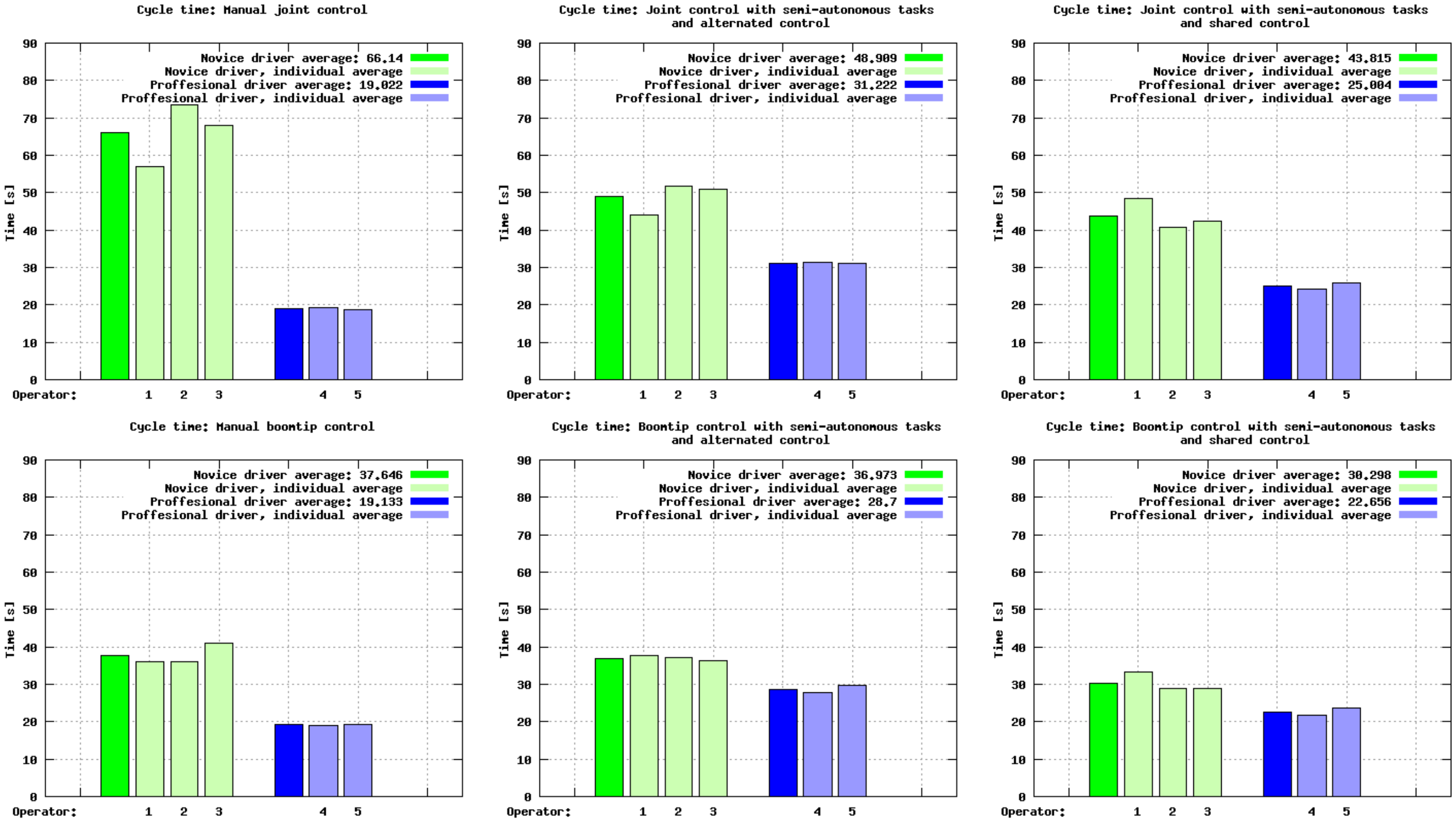


Figure 19: Work cycle average with individual work cycle average for each operator.

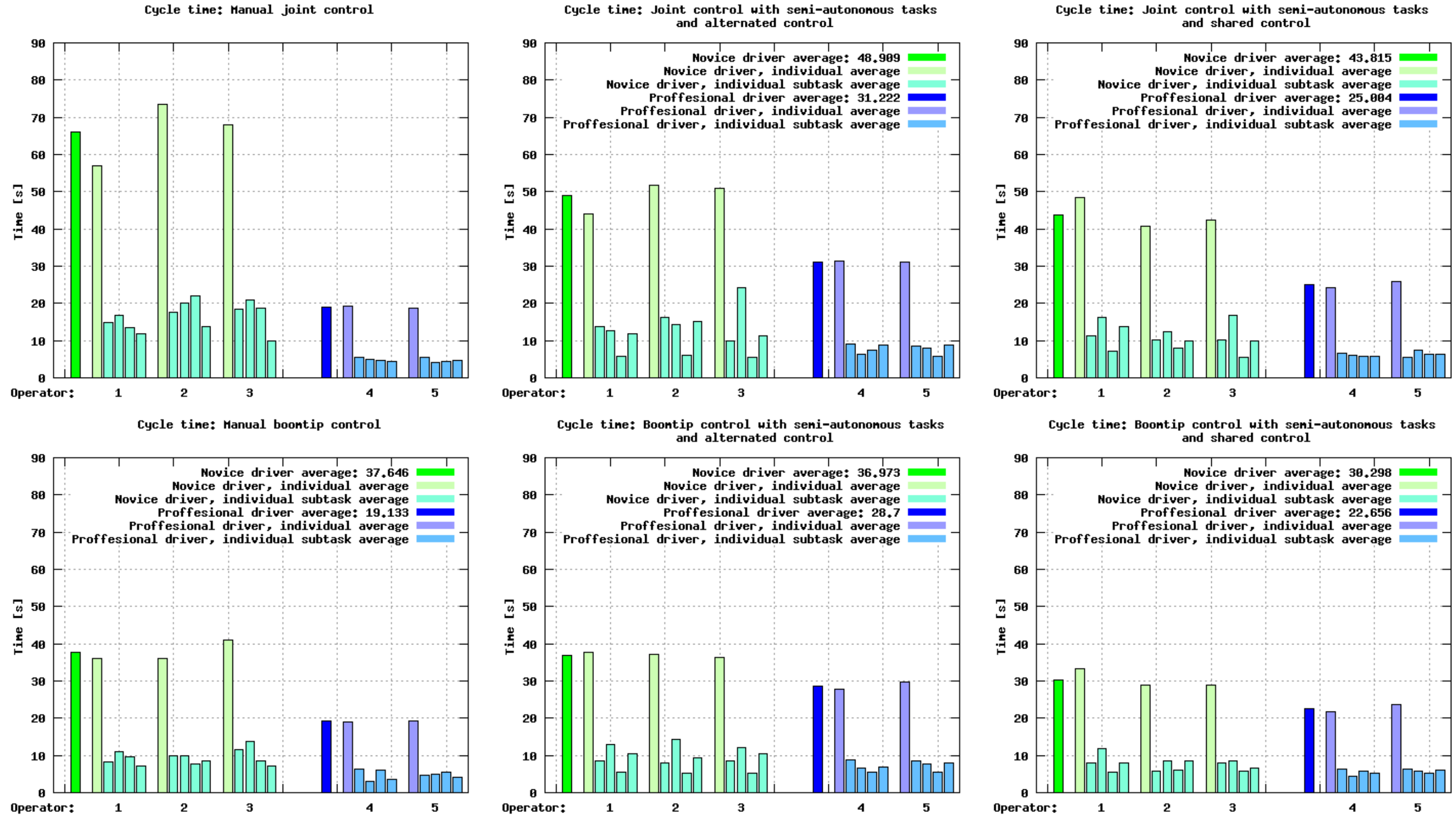


Figure 20: Total work cycle average with work cycle average and subtask average for each individual operator. Subtasks are in the order: *go out from the load bunk*, *grab logs*, *go back to the load bunk* and *release logs*.

6.2 Analysis of boom–tip vibrations

A boom–tip velocity is computed form the measured joint positions. The boom–tip velocity is then heavily filtered to get the ideal boom–tip velocity $\mathbf{v}_{ideal}$. As a measure for boom–tip vibrations during an entire test series, we use the time–normalized integral

$$\frac{1}{t_1 - t_0} \int_{t_0}^{t_1} \left| |\mathbf{v}| - |\mathbf{v}_{ideal}| \right|^4 dt$$

The average of four series of manual joint control, two series each from the two professional operators, is assumed to be the ideal vibration measure. A test series is then normalized with the ideal vibration measure, table 2 show normalized vibration measurements from all test series of all operators.

Joint control

	Manual control		**Traded control**		**Shared control**	
Operator	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
1	0.35961	1.5423		2.1166	1.9243	1.7170
2	0.37134	1.7266	1.0025	1.4733	1.2616	1.0891
3	0.70851	0.83108	3.9278	2.6967	2.5993	0.9947
4	2.4628	5.5363	2.6370	16.568	2.4343	2.4696
5	0.8239	2.8511	14.413	7.6924	2.1159	3.3290

Boom–tip control

	Manual control		**Traded control**		**Shared control**	
Operator	Series 7	Series 8	Series 3	Series 9	Series 10	Series 11
1	1.6755	2.1296	0.6222	3.2143	0.73466	0.55486
2	3.1668	2.8141	1.3306	0.87184	1.8225	0.72897
3	1.2021	1.9757	0.88935	0.38303	0.42980	0.26321
4	5.4697	2.4010	0.67574	0.86011	0.64634	2.2597
5	3.9350	7.9683	0.87864	3.6802	0.72212	1.4020

Table 2: Normalized vibration measurements from each operator.

When looking at boom–tip vibrations in transitions between manual and autonomous operation, two second before and two seconds after the transition is considered. The time–normalized integral of the squared difference of the estimated velocity and the ideal velocity is used as a vibration measurement. The average of transition vibration measurements for each test series are compiled in table 3.

Joint control

	Traded control		Shared control	
Operator	Series 3	Series 4	Series 5	Series 6
1		0.01501	0.01270	0.01340
2	0.00786	0.01162	0.01432	0.01235
3	0.01047	0.01427	0.01643	0.005818
4	0.01091	0.03084	0.01539	0.01103
5	0.03228	0.019575	0.00965	0.01176

Boom–tip control

	Traded control		Shared control	
Operator	Series 9	Series 10	Series 11	Series 12
1	0.01005	0.02269	0.01204	0.01124
2	0.01185	0.01411	0.01499	0.01108
3	0.01024	0.00694	0.006992	0.00808
4	0.00693	0.00946	0.01067	0.01963
5	0.00899	0.01714	0.0893	0.01300

Table 3: Shaking in transitions.

6.3 Operator experience

After completing the test, the subjects had to fill in a form concerning their experience from the test. Questions one to nine were on the form of estimating the experience from different moments on a scale from one to ten. Where ten corresponds to the most positive answer, five to a neutral answer and one to the most negative answer. Question ten asks which control method of conventional joint control and boom–tip control the subject would use together with autonomous tasks. In question eleven the subject can leave additional comments. A complete review of the forms are given in appendix A.

When comparing intuitiveness of conventional joint control and boom–tip control the professional operators perceive no difference while the inexperienced perceive boom–tip control easier and more intuitive. The professional operators as well as the inexperienced operators both believe that the precision is lower with boom–tip control, though the answers were very scattered from the inexperienced operators. From additional comments it can be found that for precision work the professional operators would like to be able to choose the crane configuration by them self. It is also mentioned that boom–tip control is like controlling a crane with parallel action. One of the inexperienced operators believe that when joint control is fully mastered, it is as intuitive as boom–tip control though boom–tip control still may have higher precision. On the other hand another inexperienced operator believes that fully mastered joint control has higher precision.

Both professional and inexperienced operators feel that autonomous tasks reduces the workload. From the additional comments it can be found that one of the professional operators believe that the small pauses in the operators working cycle introduce by autonomous tasks can be used to concentrate on the next pile of logs and also move the forwarder towards the next pile of logs. It is also preferable with autonomous control of the grapple. Two of the inexperienced operators found that the pauses introduced by autonomous tasks gave an opportunity to drop the concentration for a moment. The third inexperienced operator had to concentrate on controlling the grapple during the autonomous tasks and did not found a substantial reduction in workload.

Concerning interaction interface and transitions between manual joint control and autonomous tasks in *shared control* mode, the inexperienced operators found it intuitive and smooth. The professional operators found the interaction interface intuitive but the transitions were found slightly jerky. The same result can be observed when manual joint control is exchanged for manual boom–tip control, except that the professional operators here found the transitions slightly smoother.

When the subjects are asked to estimate the advantage of a fully developed semi–autonomous crane control for a professional operator, the two professional operators believe it will be a great advantage while the group of inexperienced operators only believe it will be a slight advantage. From the additional comments it can be found that the inexperienced operators believe that the professional operators are as fast or faster than the autonomous tasks, although the workload may be reduced. One of the professional operators point out the benefits of engaging in other tasks during the autonomous tasks.

When the subjects estimate the advantage of a fully developed semi–autonomous crane control for an inexperienced operator the group of inexperienced operators believe it will be a clear advantage while the group of professional operators only believe it will be a slight advantage. In the comments from a professional operator it is found that the fact that the autonomous tasks are the easy part of the work cycle while the complicated tasks still remains, which will give the inexperienced operator only a slight advantage. One of the inexperienced operators points out that an inexperienced operator would be able to cope with longer shifts due to the reduction of workload.

Finally the operators were asked to choose the most preferable control method of joint control and boom–tip control that they would prefer to use along with autonomous operation and *shared control*. Here all the operators answered boom–tip control except from one of the professional operators.

7 Conclusions

This study shows that semi–autonomous operation of a forwarder crane is feasible and that both inexperienced and professional operators can benefit from it. The time study shows that the inexperienced operators increase in performance by a factor two with boom–tip control together with *shared control* as compared to manual joint control. For professional operators the performance decrease somewhat. Compared to manual operation, *shared control* together with boom–tip control is 19% slower for professional operators. Considering that professional operators has years of training in manual operation, one might expected that with training in semi-autonomous operation the performance may be equally well or even better than with manual operation. The form survey shows that both inexperienced and professional operators believe that a fully developed semi–autonomous crane control would reduce the workload. It also shows that both professional and inexperienced operators found the smoothness in transitions between manual and autonomous operation satisfactory.

7.1 Limitations

Since the inexperienced operators only has one hour of training it is a risk that their ability to operate the crane improve significantly during the experiment. This may give better results for all boom–tip control series, which are performed after the joint control series.

The joint control implementation used together with *traded* and *shared control* suffer from bumpiness and jitter which may have a negative effect on the results.

7.2 Future work

This study shows benefits with semi–autonomous operation for both inexperienced and professional operators. However, it can not show that a professional operator is equally fast or faster with semi–autonomous operation compared to manual operation. A study focused on professional operators to show that semi–autonomous operation can increase their productivity is desirable.

This implementation requires robust sensor solutions at the crane which may increase the production cost.

A Operator experience

1. How do you experience control of the crane with boom–tip control compared to conventional joint control?

1 – more difficult, non–intuitive	5 – no difference	10 – easier, more intuitive

	Samples			Average
Professional operators (operators 1 and 2)	5	5		5.00
Novice operators (operators 3, 4 and 5)	7	8	10	8.33

Operator comments

Operator	Professional operator comments
1	Boom–tip control is like controlling a crane with parallel action.
2	-

Operator	Novice operator comments
3	When you can handle joint control there is probably no big difference.
4	Much easier from the beginning.
5	-

2. Estimate how the precision is influenced with boom–tip control compared to conventional joint control?

1 – lower precision	5 – no difference	10 – higher precision

	Samples			Average
Professional operators (operators 1 and 2)	4	5		4.50
Novice operators (operators 3, 4 and 5)	8	4	2	4.66

Operator comments

Operator	**Professional operator comments**
1	May be less precision when sorting the logs, because the cranes configuration can not be selected by the operator.
2	-

Operator	**Novice operator comments**
3	Boom–tip control may be more useful in precision motions compared to more rough motions.
4	A professional operator may feel a difference, but i did not notice any difference.
5	Supposed that the operator can handle joint control it has higher precision. There was some jitter with boom–tip control.

3. Do you experience that autonomous tasks in the work cycle reduce the workload?

1 – an increased workload 5 – no difference 10 – a clear reduction of workload

	Samples			Average
Professional operators (operators 1 and 2)	7	8		7.50
Novice operators (operators 3, 4 and 5)	6	9	10	8.33

Operator comments

Operator	**Professional operator comments**
1	Gives an opportunity to look at something else than the crane for some seconds. Though it is also preferable with autonomous control of the grapple.
2	-

Operator	**Novice operator comments**
3	Most of the time during the autonomous motion was spent on controlling the grapple, consequently I had not so much advantage of the autonomous tasks.
4	One can relax while the crane take care of it self, though the orientation of the log has to be controlled manually.
5	Manual control of the crane requires a lot of concentration for me, therefore the small pauses is very relaxing and reduces the workload.

4. How is the interaction interface to the autonomous system with joint control together with shared control?

1 – incomprehensible	5 – neither nor	10 – intuitive/natural

	Samples			Average
Professional operators (operators 1 and 2)	9	7		8.00
Novice operators (operators 3, 4 and 5)	9	9	10	9.33

Operator comments

Operator	**Professional operator comments**
1	Surprisingly well! The take over from an autonomous task works well. Though at the beginning there may be a risk that the operator follows the autonomous task with the joysticks, but with some training that is probably not a problem.
2	-

Operator	**Novice operator comments**
3	Felt good.
4	Most of the time I did not influence the autonomous task.
5	-

5. How is the interaction interface to the autonomous system with boom–tip control together with shared control?

1 – incomprehensible	5 – neither nor	10 – intuitive/natural

	Samples			Average
Professional operators (operators 1 and 2)	9	8		8.50
Novice operators (operators 3, 4 and 5)	9	9	10	9.33

Operator comments

Operator	Professional operator comments
1	Surprisingly well! The take over from an autonomous task works well. Though at the beginning there may be a risk that the operator follows the autonomous task with the joysticks, but with some training that is probably not a problem.
2	-

Operator	Novice operator comments
3	Felt good.
4	Most of the time I did not influence the autonomous task.
5	-

6. Estimate the quality in the transitions between manual and autonomous operation in joint control together with shared control.

1 – annoying/jerky   5 – neither nor   10 – even and smooth

	Samples			Average
Professional operators (operators 1 and 2)	5	4		4.50
Novice operators (operators 3, 4 and 5)	8	8	10	8.66

Operator comments

Operator	**Professional operator comments**
1	It usually worked good, but sometimes it was jerky. However, it was better than I expected.
2	Jerky

Operator	**Novice operator comments**
3	Felt good together with *shared control*, but otherwise it was jerky.
4	It was very smooth to take over control from the autonomous tasks.
5	-

7. Estimate the quality in the transitions between manual and autonomous operation in boom–tip control together with shared control.

1 – annoying/jerky	5 – neither nor	10 – even and smooth

	Samples			Average
Professional operators (operators 1 and 2)	5	8		6.50
Novice operators (operators 3, 4 and 5)	8	9	10	9.00

Operator comments

Operator	Professional operator comments
1	It usually worked good, but sometimes it was jerky. However, it was better than I expected.
2	Jerky

Operator	Novice operator comments
3	Felt good together with *shared control*, but otherwise it was jerky.
4	Slightly better than the corresponding for joint control.
5	-

8. Estimate the advantage of a fully developed semi–autonomous crane control for a professional operator.

1 – clear degradation	5 – no advantage	10 – clear advantage

	Samples			Average
Professional operators (operators 1 and 2)	8	9		8.50
Novice operators (operators 3, 4 and 5)	6	8	6	6.66

Operator comments

Operator	Professional operator comments
1	A clear advantage in final felling, especially when the logs are sparsely located at the felling area. Then the operator can concentrate on find and drive to the next pile of logs. However, to use the same target point all the time for the autonomous tasks make the use of them very limited.
2	-

Operator	Novice operator comments
3	A professional operator is probably not faster, but it may reduce the workload.
4	They get some relaxing pauses, but the autonomous motion should probably be learned with a lot of training.
5	It is very difficult for me to estimate how much concentration needed for a professional operator to manually control the crane. For a half learned operator it should be a great advantage.

9. Estimate the advantage of a fully developed semi–autonomous crane control for a novice operator.

1 – clear degradation	5 – no advantage	10 – clear advantage

	Samples			Average
Professional operators (operators 1 and 2)	6	6		6.00
Novice operators (operators 3, 4 and 5)	9	10	10	9.66

Operator comments

Operator	Professional operator comments
1	A novice operator may have less advantage because it is rather basic tasks that is automated. The difficult tasks are to grab the logs, sort them and put them in the load bunk. A novice operator may not be capable of using the ”free time” introduced by the autonomous tasks to other tasks.
2	-

Operator	Novice operator comments
3	-.
4	Helped a lot.
5	I believe that semi–autonomous operation should make it a lot easier for a novice operator. Especially regarding to how long shifts the operator can handle.

10. Which operating mode, joint control or boom–tip control, should you use together with autonomous tasks, given that operating modes and autonomous tasks are smooth and without artifacts?

Professional operators

	Joint control	**Boom–tip control**
1	X	
2		X

Novice operators

	Joint control	**Boom–tip control**
3		X
4		X
5		X

Operator comments

Operator	**Professional operator comments**
1	But for a novice operator it is probably easier with boom–tip control.
2	-

Operator	**Novice operator comments**
3	-.
4	-
5	-

11. Additional thoughts and suggestions on improvements of the control methods and opinion on how the experiments was carried out.

Operator comments

Operator	**Professional operator comments**
1	Pleasantly surprised of how well the boom–tip control works.
2	-

Operator	**Novice operator comments**
3	-.
4	-
5	-

B Experiment figures

B.1 Operator 1

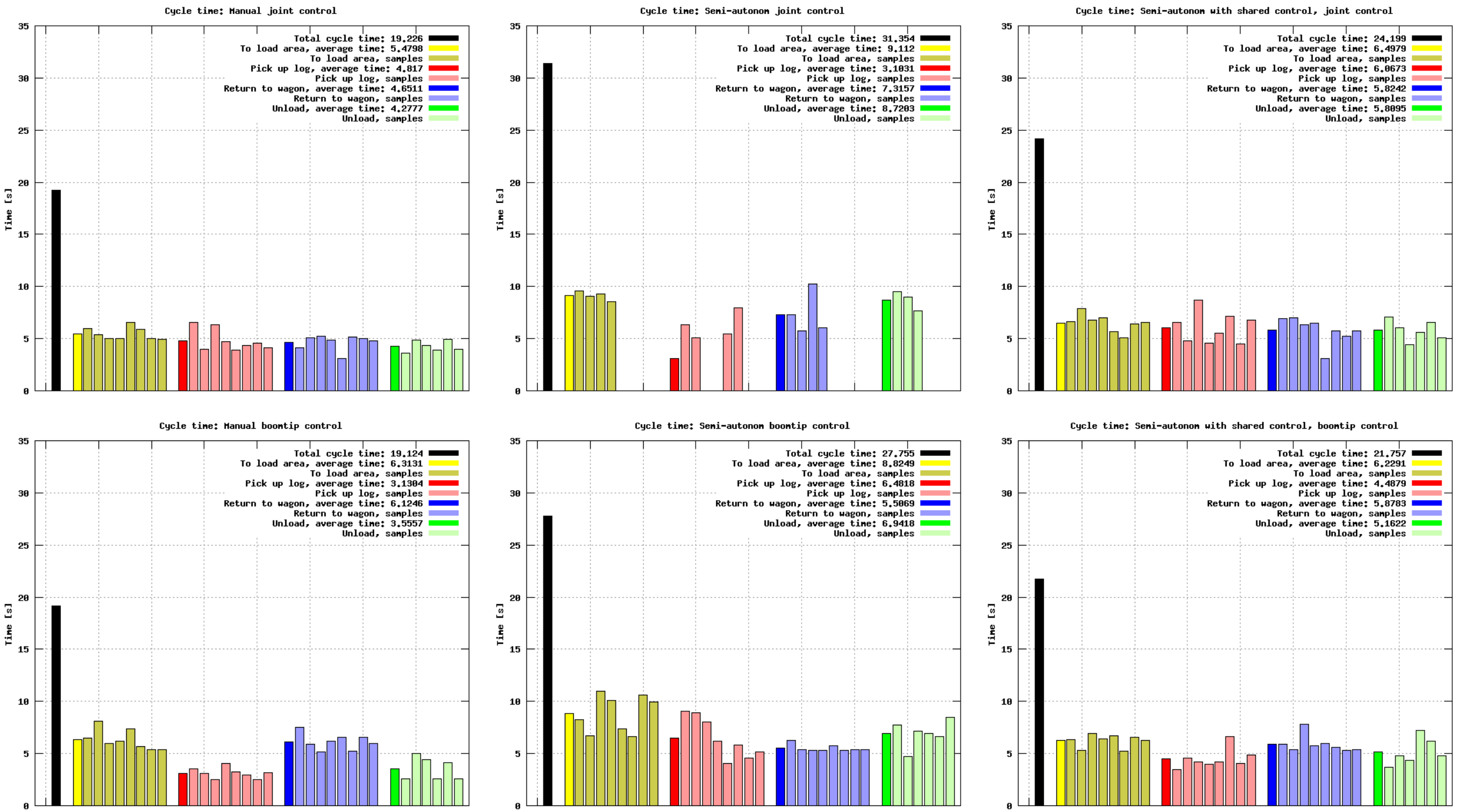
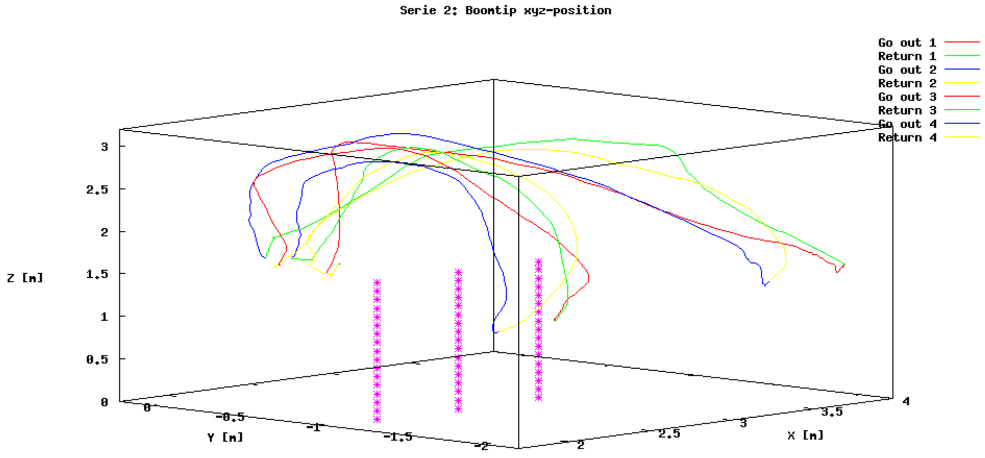
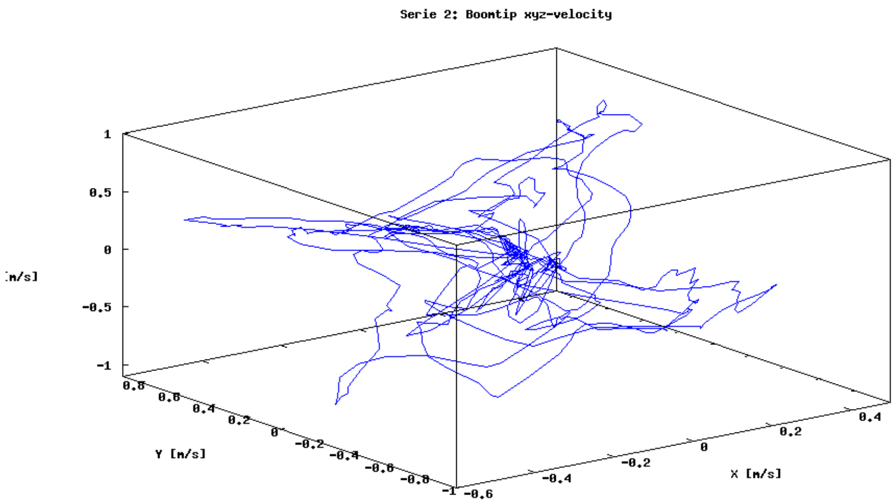


Figure 21: Operator 1 summary

B.1.1 Samples

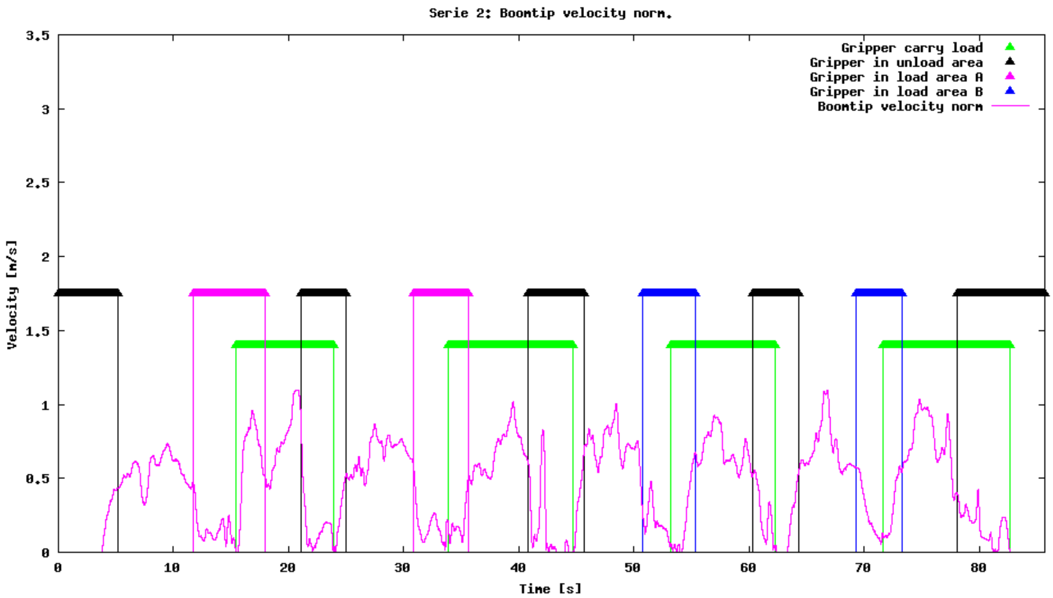


(a) Operator 1 , series 2 – Boom–tip position, manual joint control.



(b) Operator 1 , serie 2 – Boom–tip velocity, manual joint control.

Figure 22



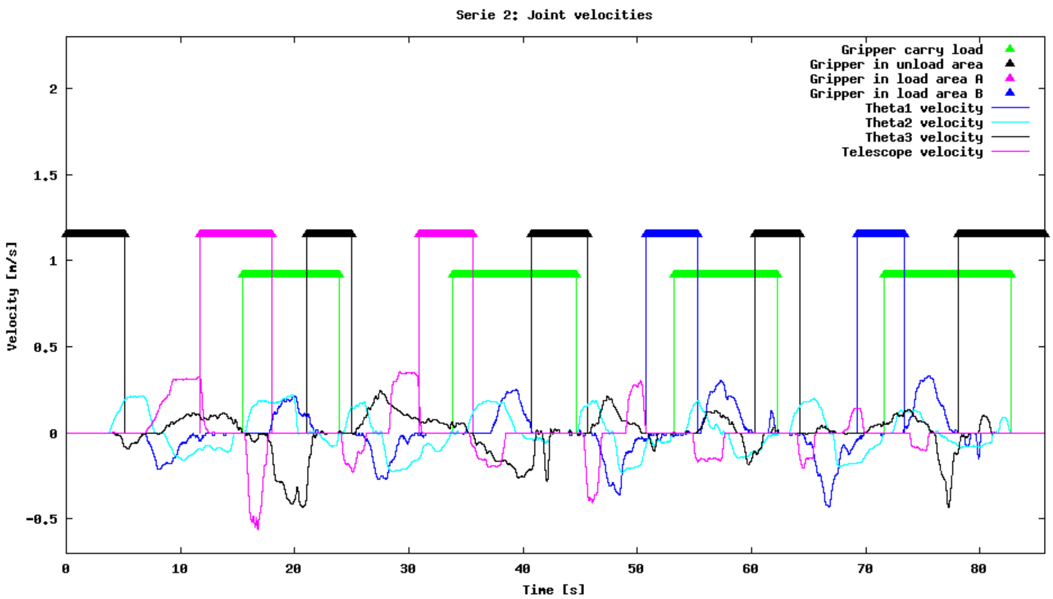
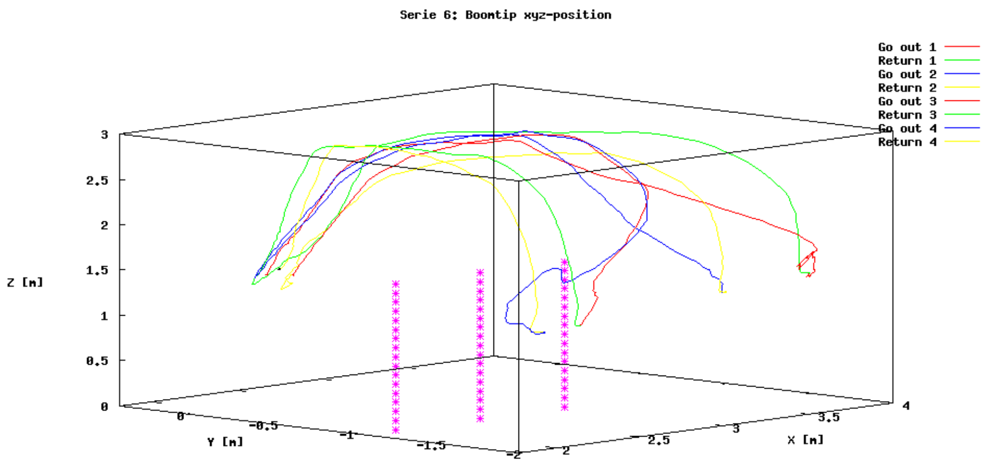
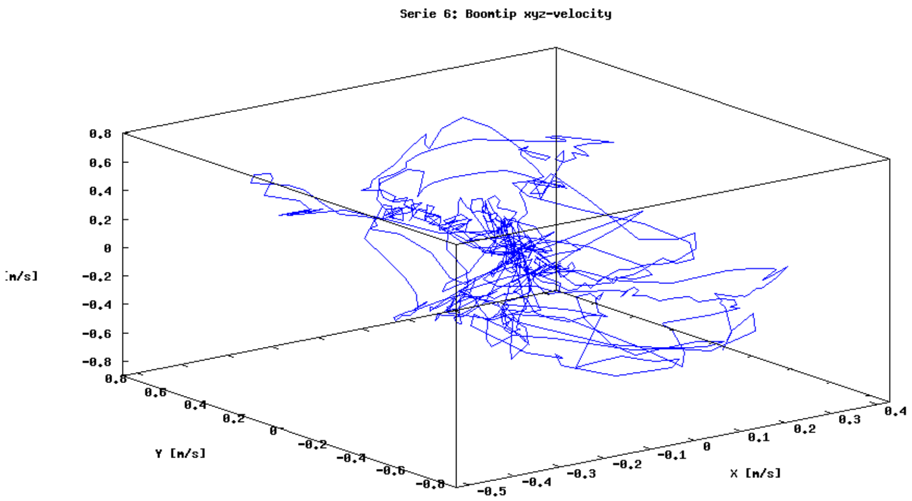


Figure 23: Operator 1 , serie 2 – Boom–tip velocity and joint velocities versus time, manual joint control

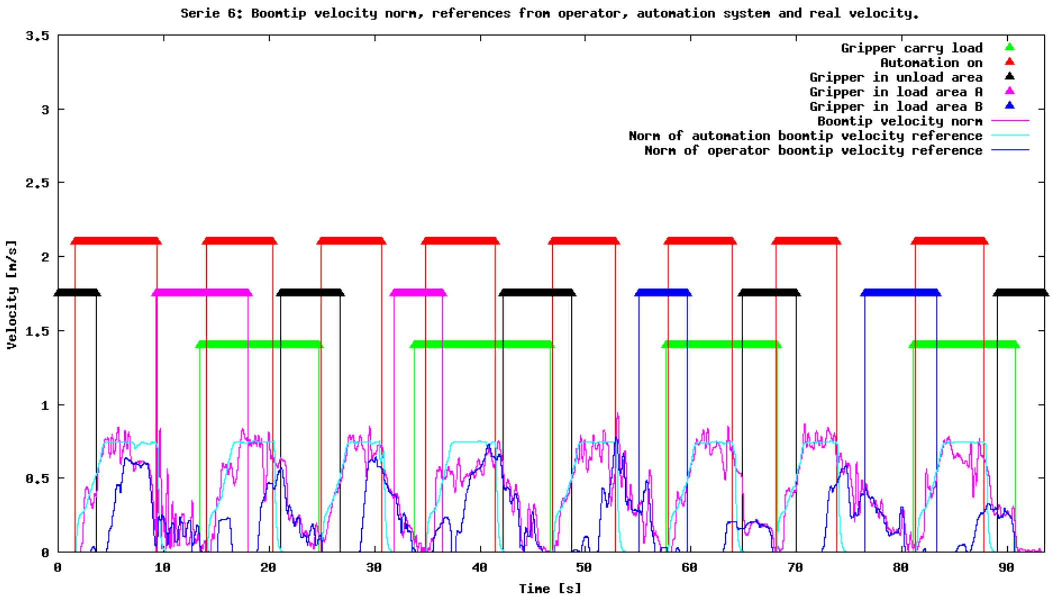


(a) Operator 1 , serie 6 – Boom–tip position, *traded control* with joint control.



(b) Operator 1 , serie 6 – Boom–tip velocity, *traded control* with joint control.

Figure 24



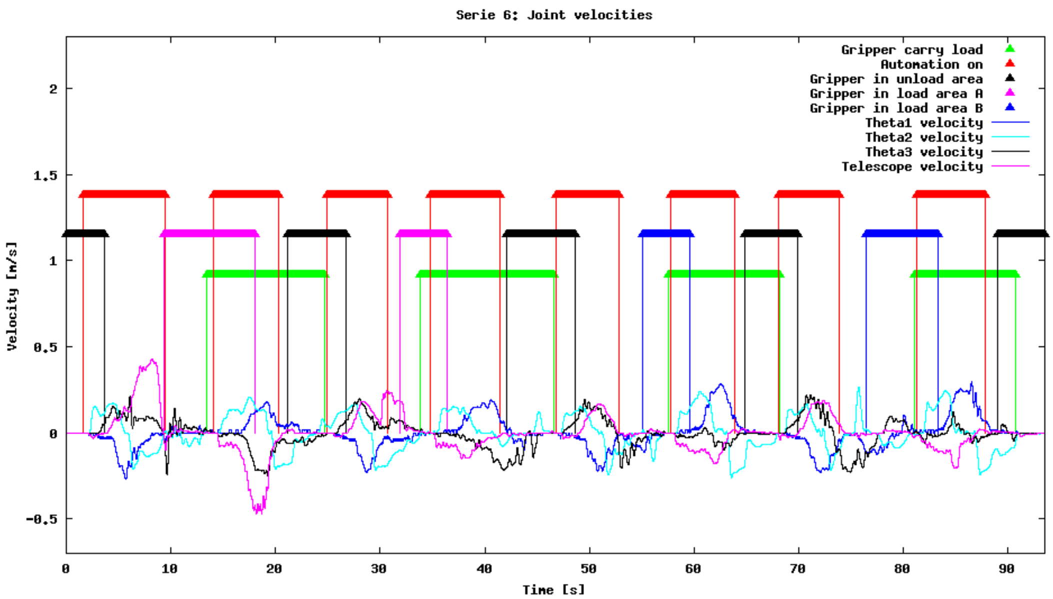
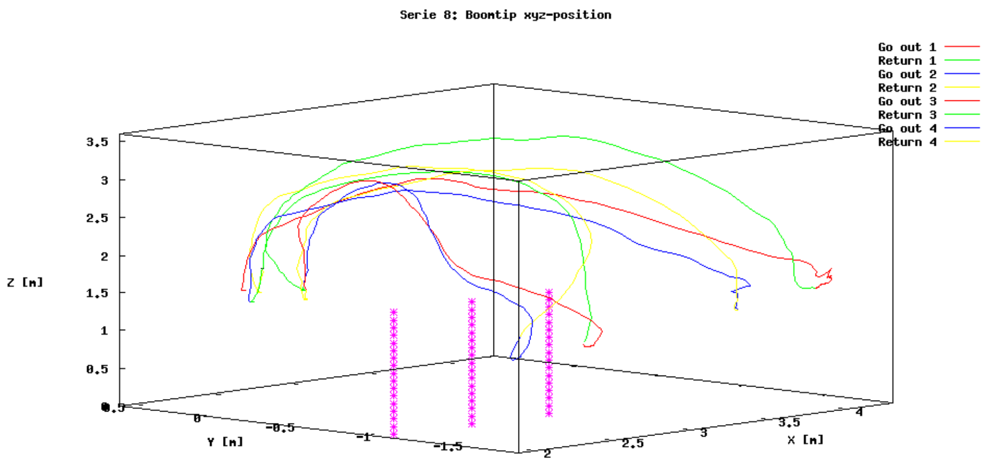
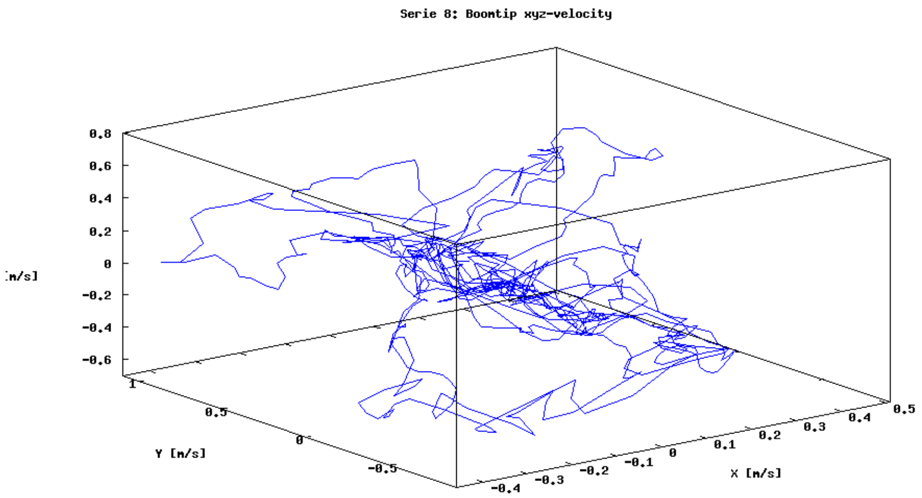


Figure 25: Operator 1 , serie 6 – Boom–tip velocity and joint velocities versus time, *traded control* with joint control

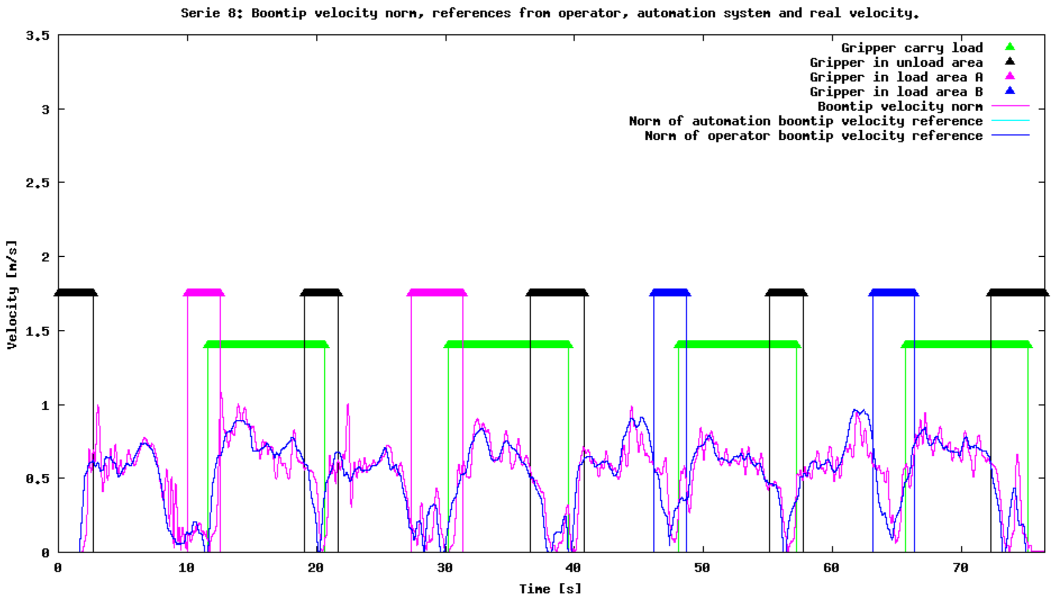


(a) Operator 1 , serie 8 – Boom–tip position, manual boom–tip control.



(b) Operator 1 , serie 8 – Boom–tip velocity, manual boom–tip control.

Figure 26



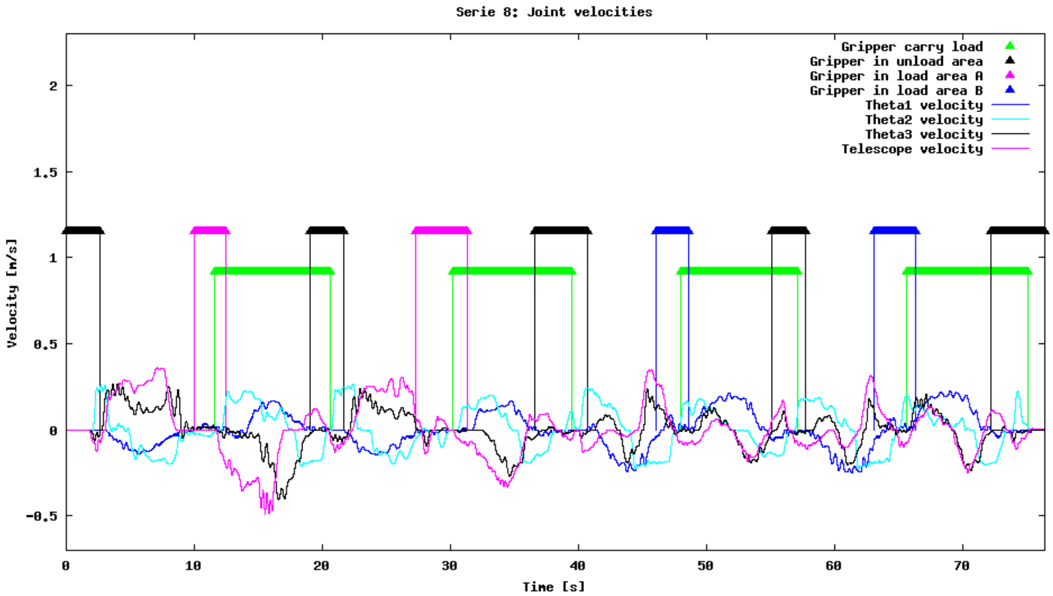
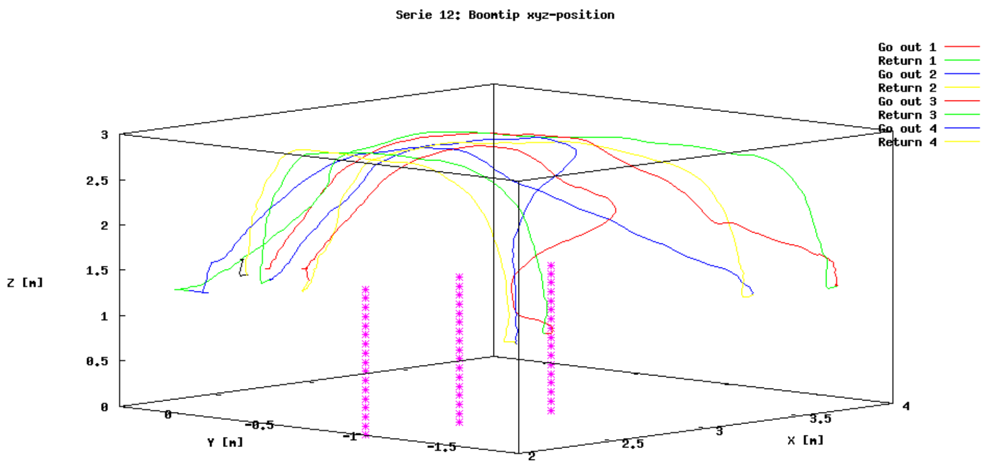
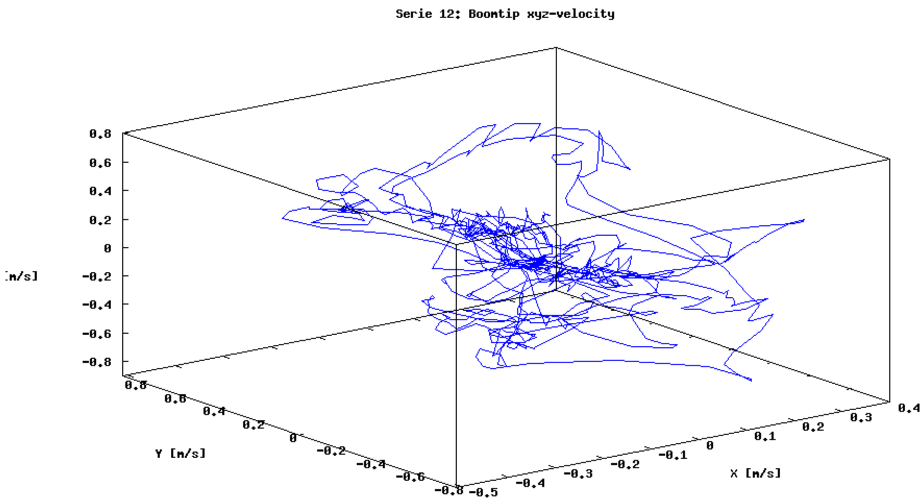


Figure 27: Operator 1 , serie 8 – Boom–tip velocity and joint velocities versus time, manual boom–tip control



(a) Operator 1 , serie 12 – Boom–tip position, *shared control* with boom–tip control.



(b) Operator 1 , serie 12 – Boom–tip velocity, *shared control* with boom–tip control.

Figure 28

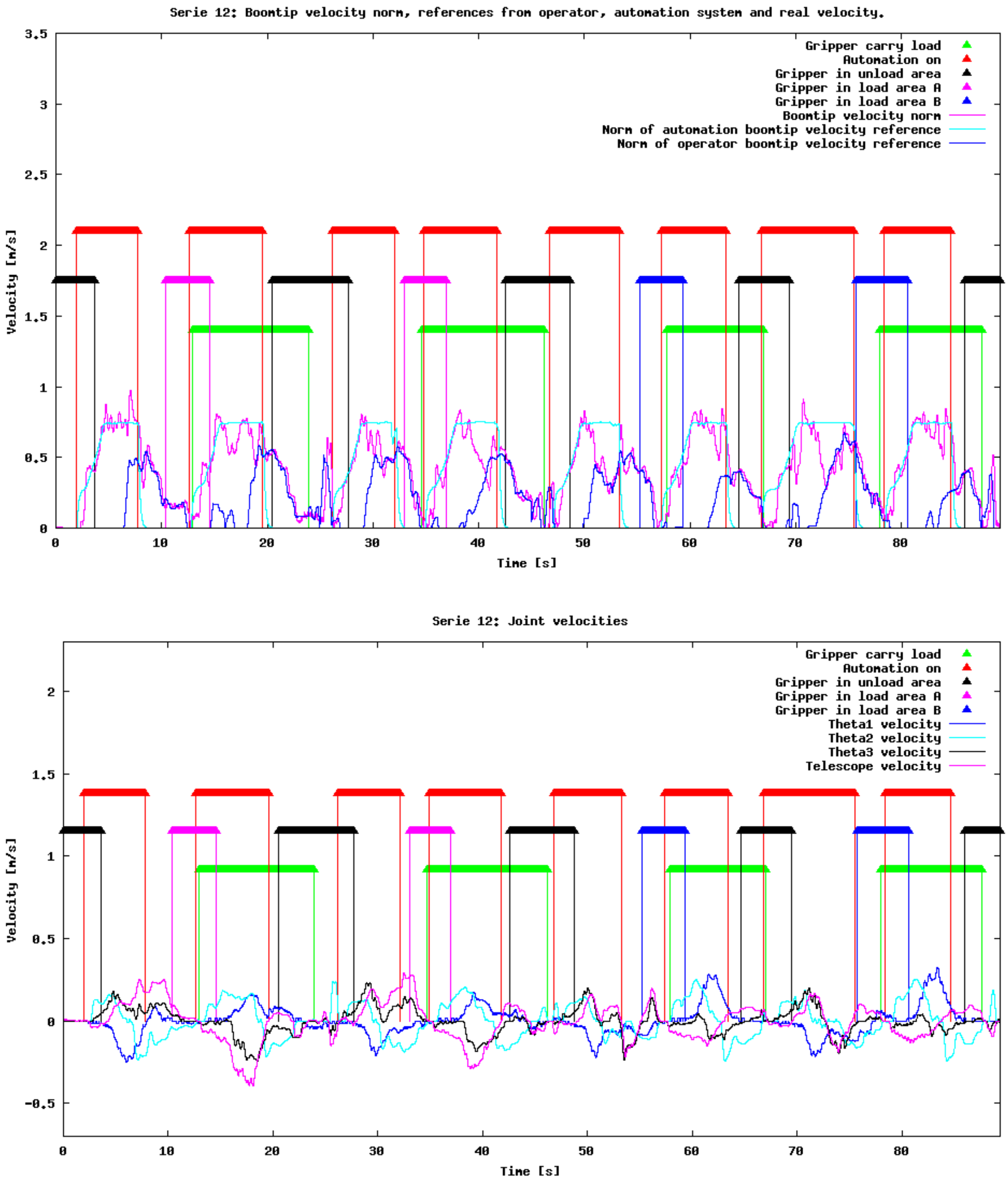
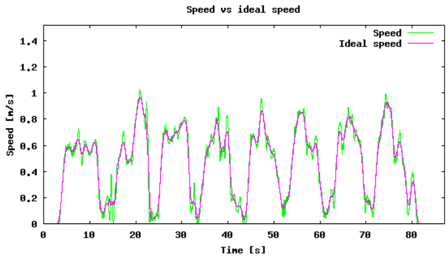
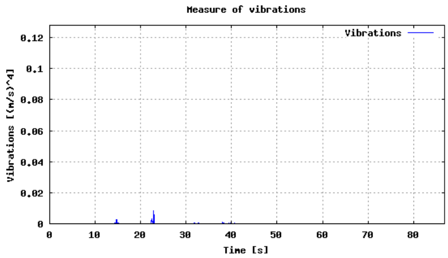


Figure 29: Operator 1 , serie 12 – Boom–tip velocity, boom–tip velocity and joint velocities versus time, *shared control* with boom–tip control

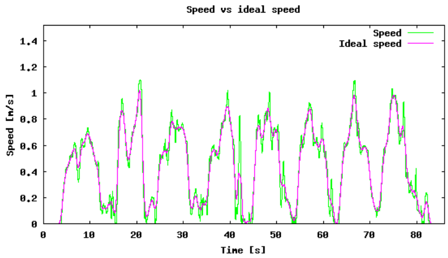
B.1.2 Boom–tip vibrations



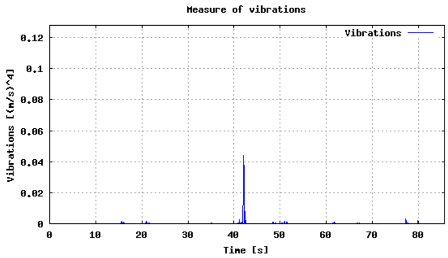
(a) Operator 1, serie 1 – Ideal speed vs actual speed.



(b) Operator 1, serie 1 – Vibrations.

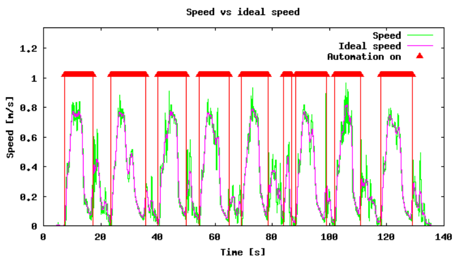


(c) Operator 1, serie 2 – Ideal speed vs actual speed.

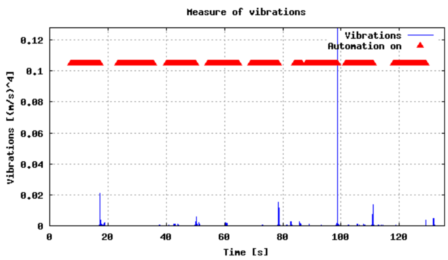


(d) Operator 1, serie 2 – Vibrations.

Figure 30: Operator 1 – Manual joint control

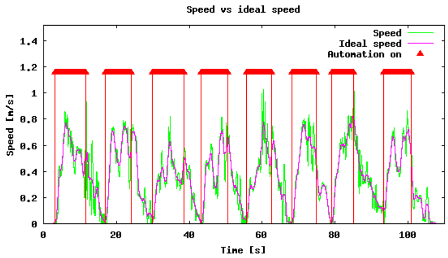


(a) Operator 1, serie 4 – Ideal speed vs actual speed.

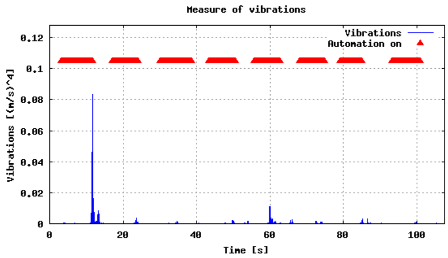


(b) Operator 1, serie 4 – Vibrations.

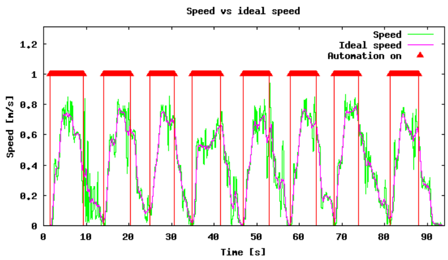
Figure 31: Operator 1 – Joint control with *traded control*.



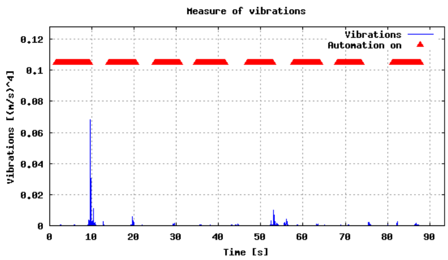
(a) Operator 1, serie 5 – Ideal speed vs actual speed.



(b) Operator 1, serie 5 – Vibrations.

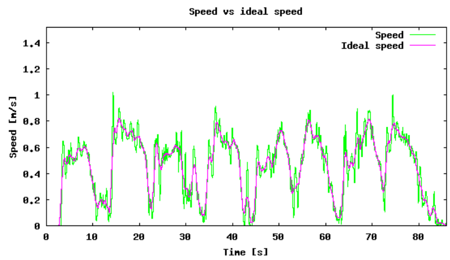


(c) Operator 1, serie 6 – Ideal speed vs actual speed.

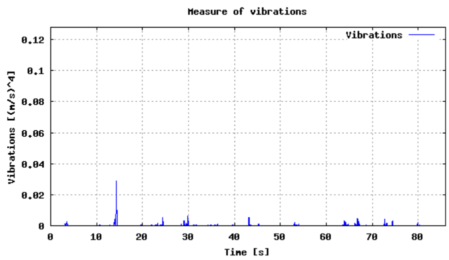


(d) Operator 1, serie 6 – Vibrations.

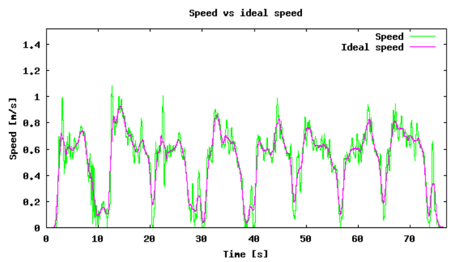
Figure 32: Operator 1 – Joint control with *shared control*.



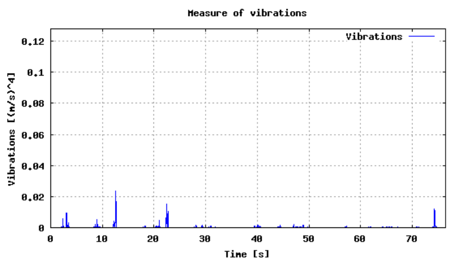
(a) Operator 1, serie 7 – Ideal speed vs actual speed.



(b) Operator 1, serie 7 – Vibrations.

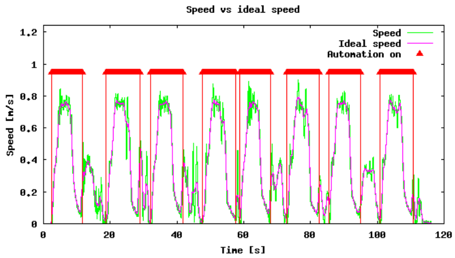


(c) Operator 1, serie 8 – Ideal speed vs actual speed.

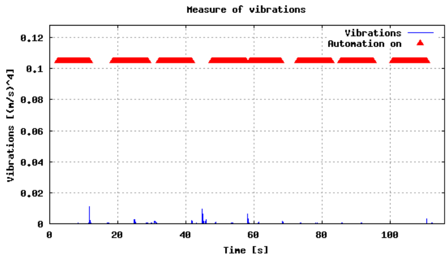


(d) Operator 1, serie 8 – Vibrations.

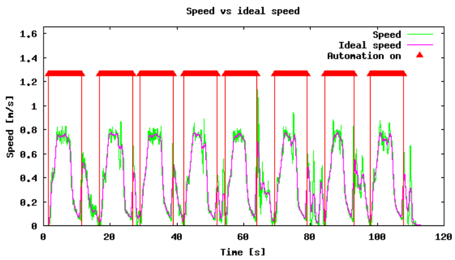
Figure 33: Operator 1 – Manual boom–tip control.



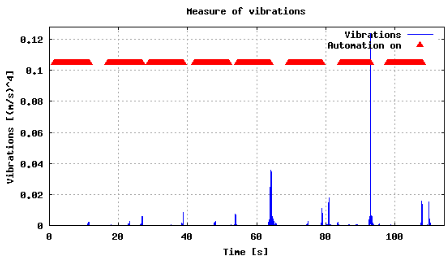
(a) Operator 1, serie 9 – Ideal speed vs actual speed.



(b) Operator 1, serie 9 – Vibrations.

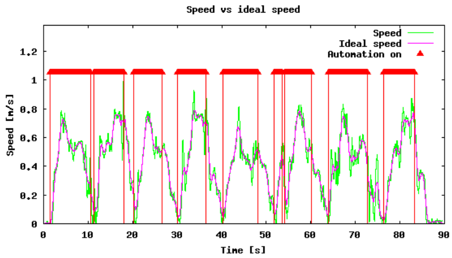


(c) Operator 1, serie 10 – Ideal speed vs actual speed.

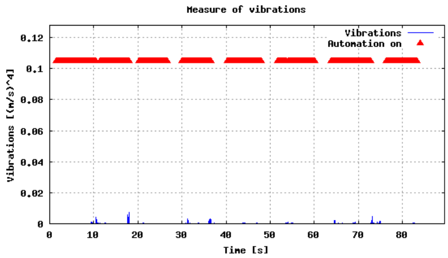


(d) Operator 1, serie 10 – Vibrations.

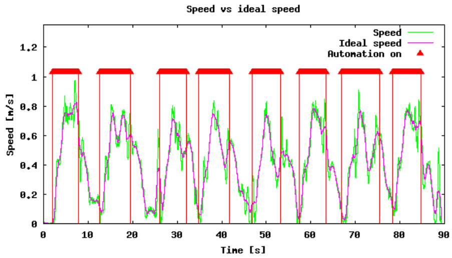
Figure 34: Operator 1 – Boom–tip control with *traded control*.



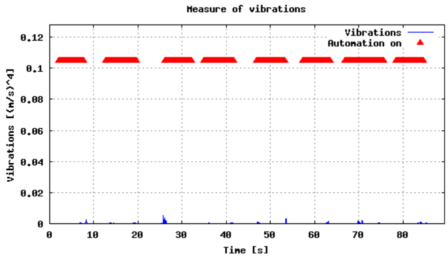
(a) Operator 1, serie 11 – Ideal speed vs actual speed.



(b) Operator 1, serie 11 – Vibrations.



(c) Operator 1, serie 12 – Ideal speed vs actual speed.



(d) Operator 1, serie 12 – Vibrations.

Figure 35: Operator 1 – Boom–tip control with *shared control*.

B.2 Operator 2

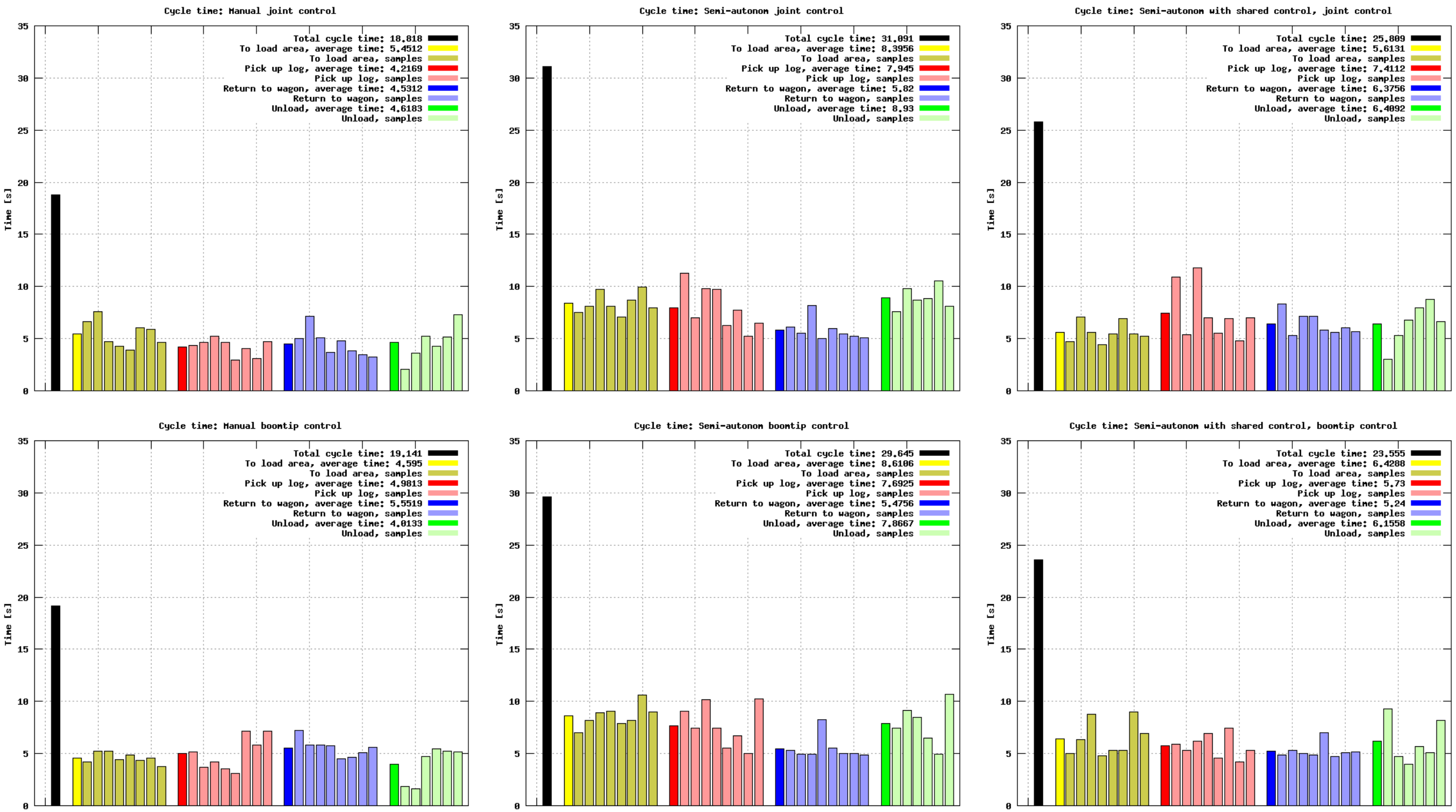
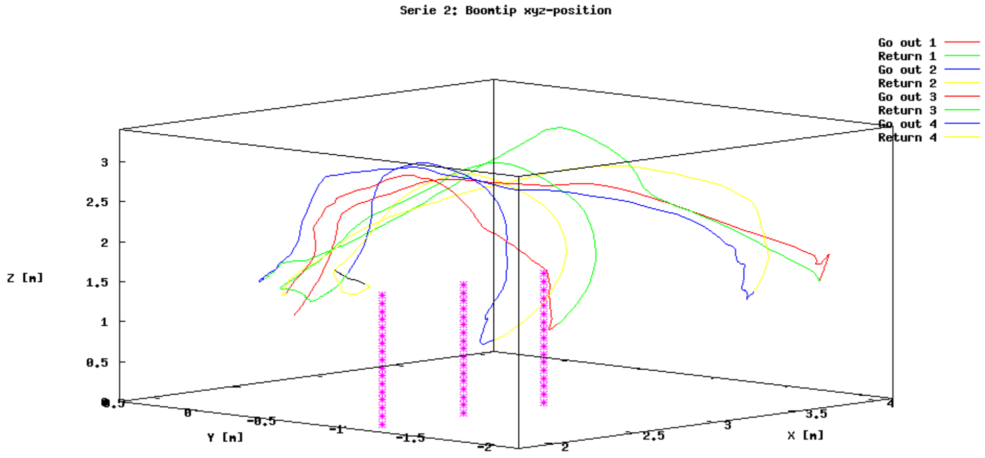
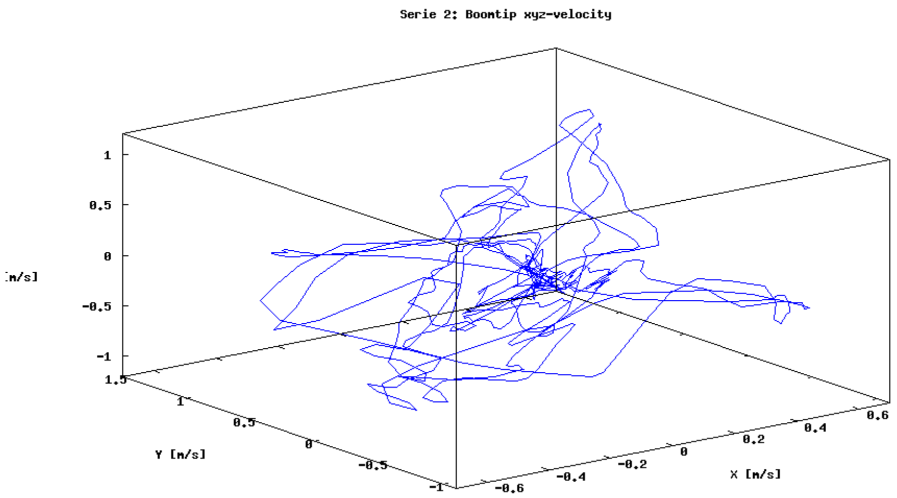


Figure 36: Operator 2 summary

B.2.1 Samples

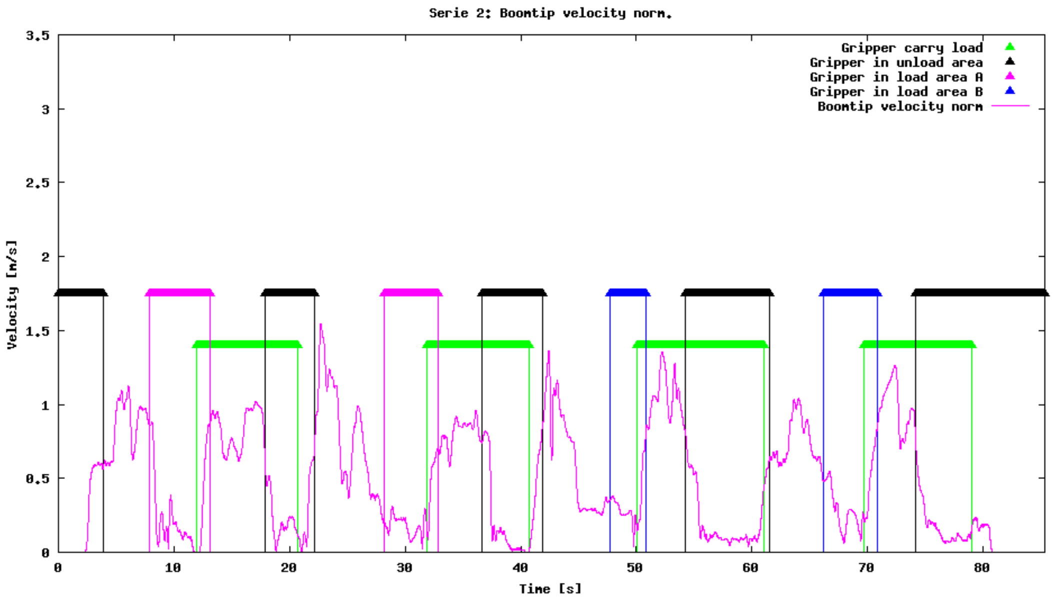


(a) Operator 2 , serie 2 – Boom–tip position, manual joint control.



(b) Operator 2 , serie 2 – Boom–tip velocity, manual joint control.

Figure 37



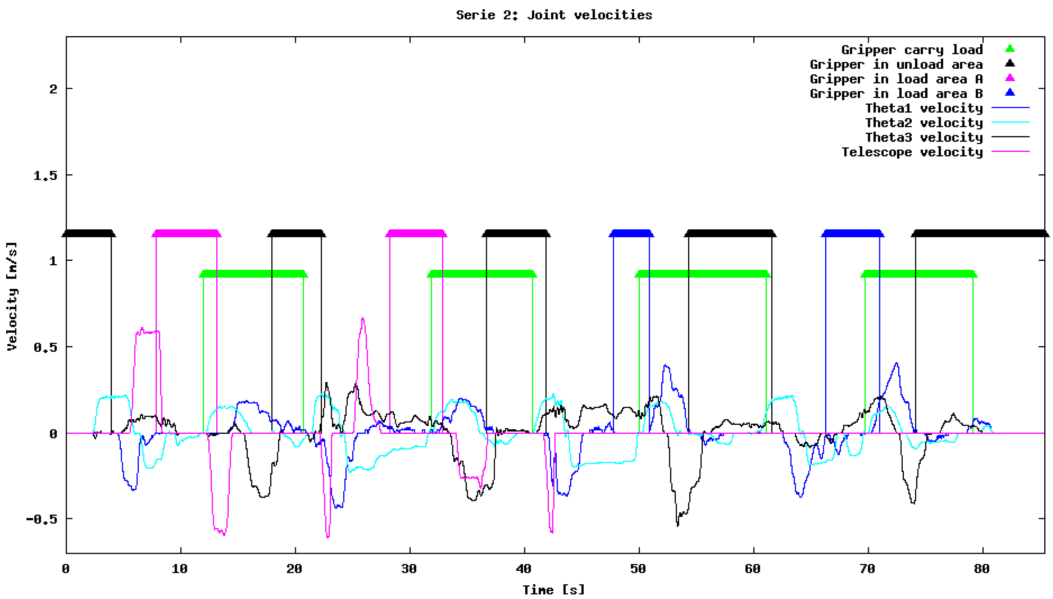
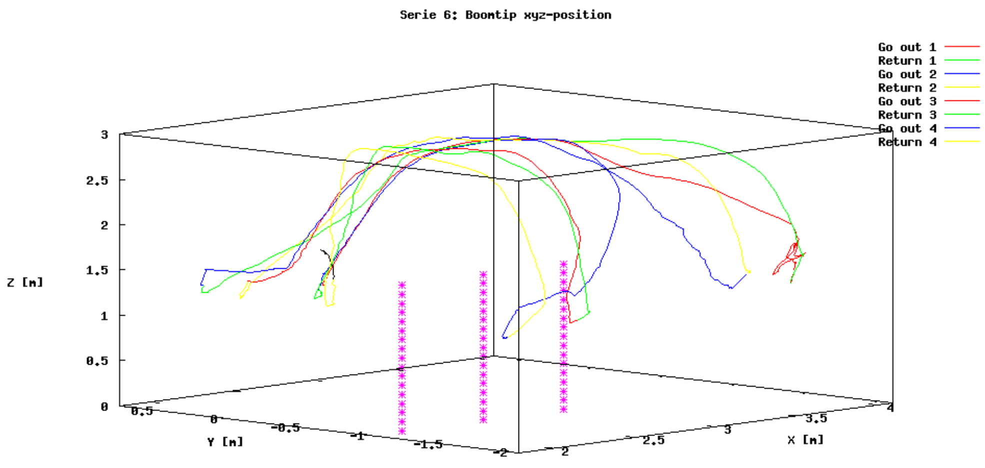
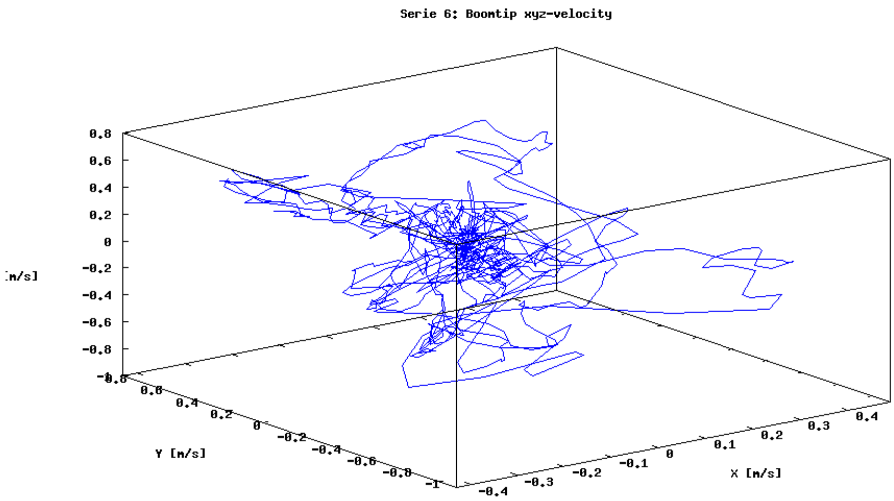


Figure 38: Operator 2 , serie 2 – Boom–tip velocity and joint velocities versus time, manual joint control

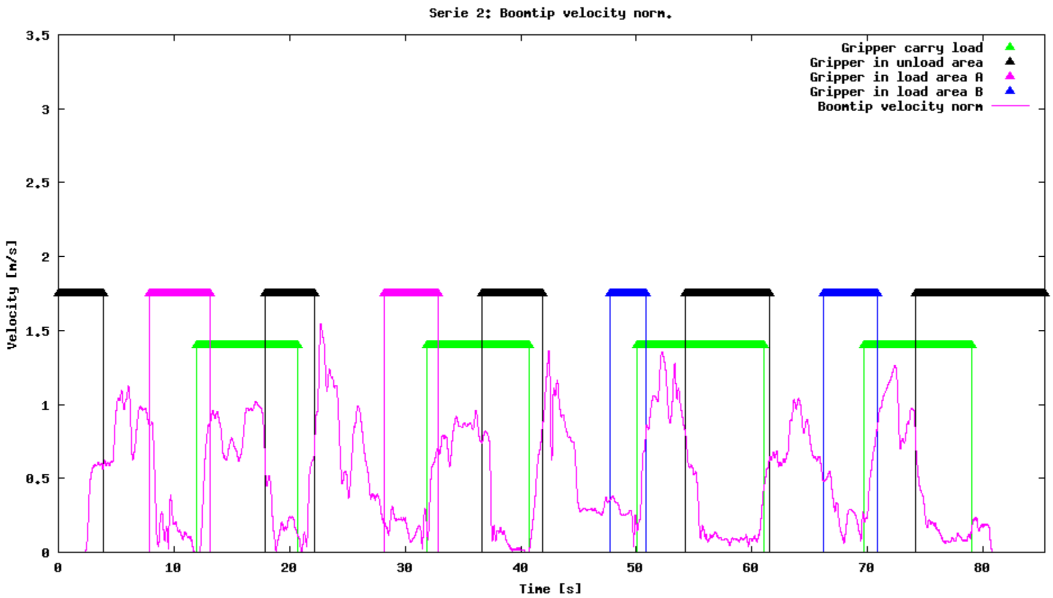


(a) Operator 2 , serie 6 – Boom–tip position, *traded control* with joint control.



(b) Operator 2 , serie 6 – Boom–tip velocity, *traded control* with joint control.

Figure 39



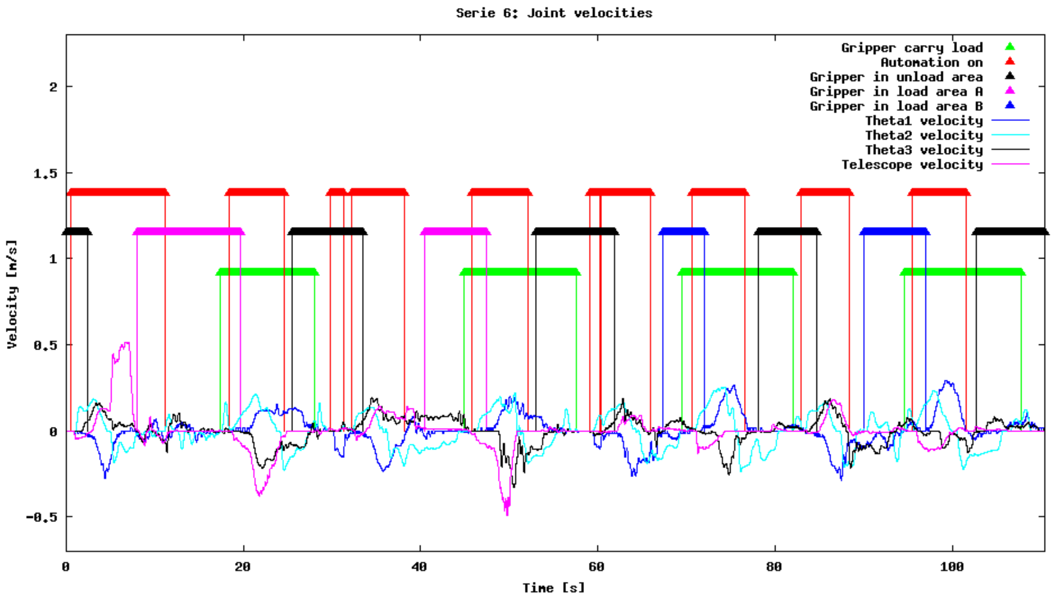
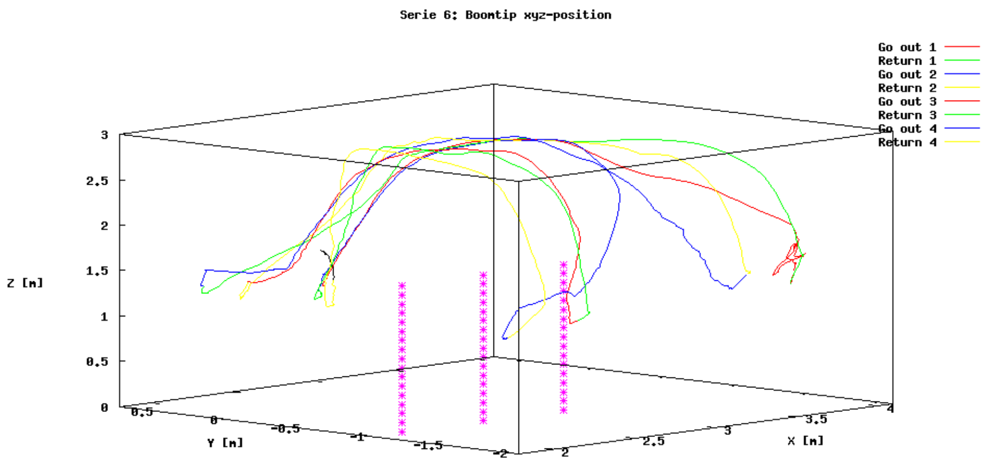
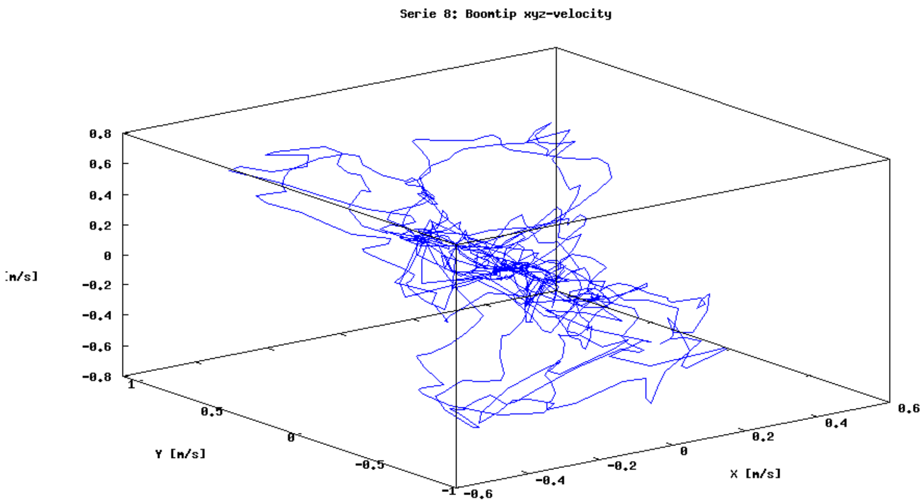


Figure 40: Operator 2 , serie 6 – Boom–tip velocity and joint velocities versus time, *traded control* with joint control

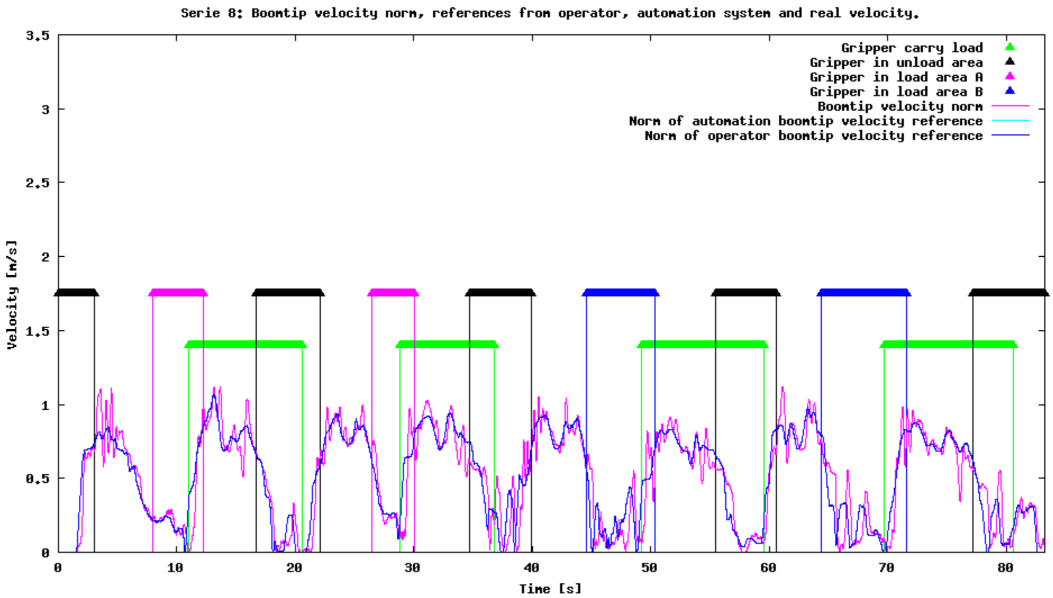


(a) Operator 2 , serie 8 – Boom–tip position, manual boom–tip control.



(b) Operator 2 , serie 8 – Boom–tip velocity, manual boom–tip control.

Figure 41



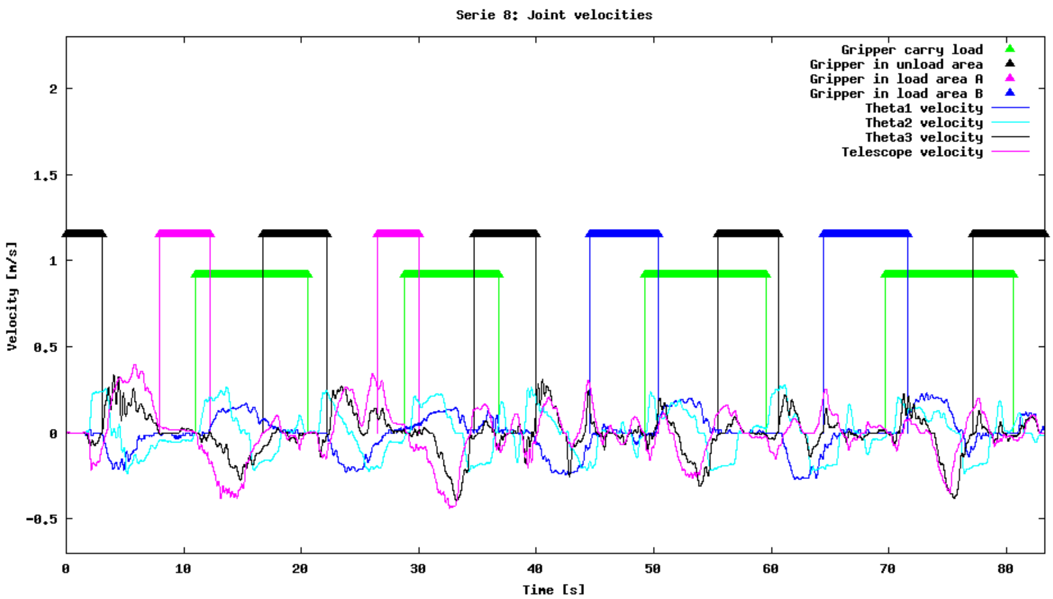
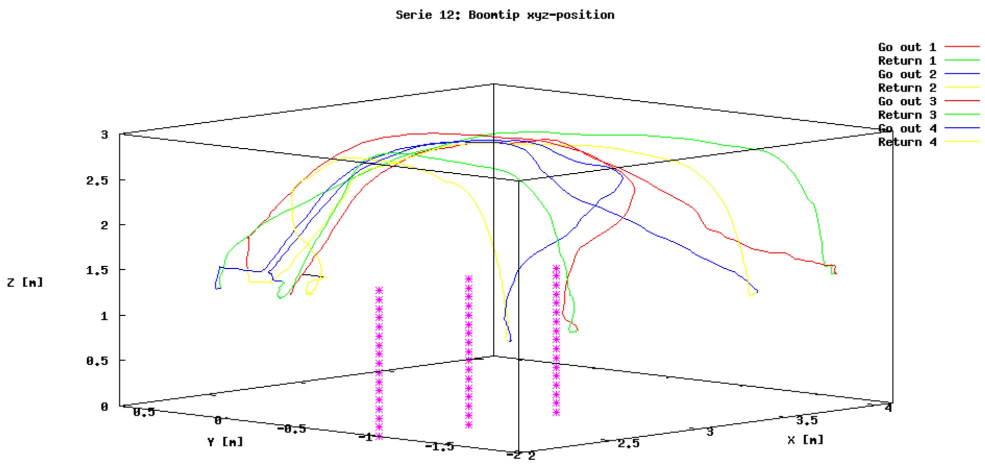
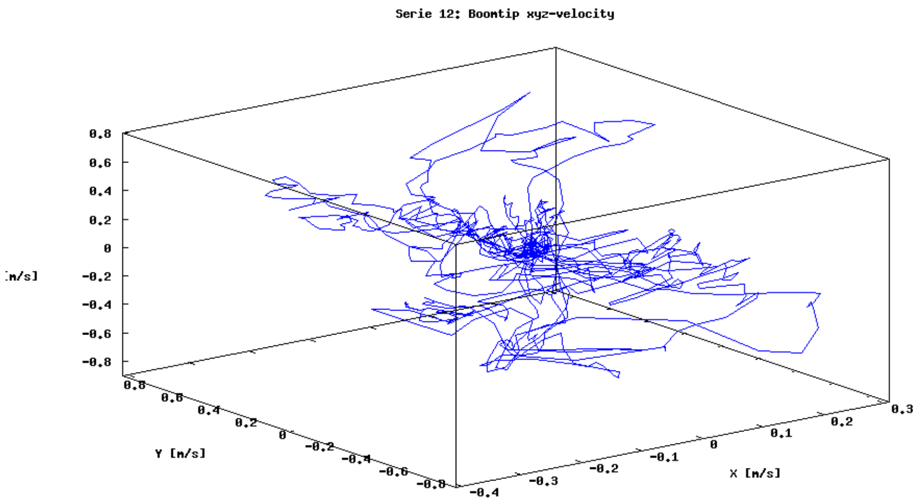


Figure 42: Operator 2 , serie 8 – Boom–tip velocity and joint velocities versus time, manual boom–tip control



(a) Operator 2 , serie 12 – Boom–tip position, *shared control* with boom–tip control.



(b) Operator 2 , serie 12 – Boom–tip velocity, *shared control* with boom–tip control.

Figure 43

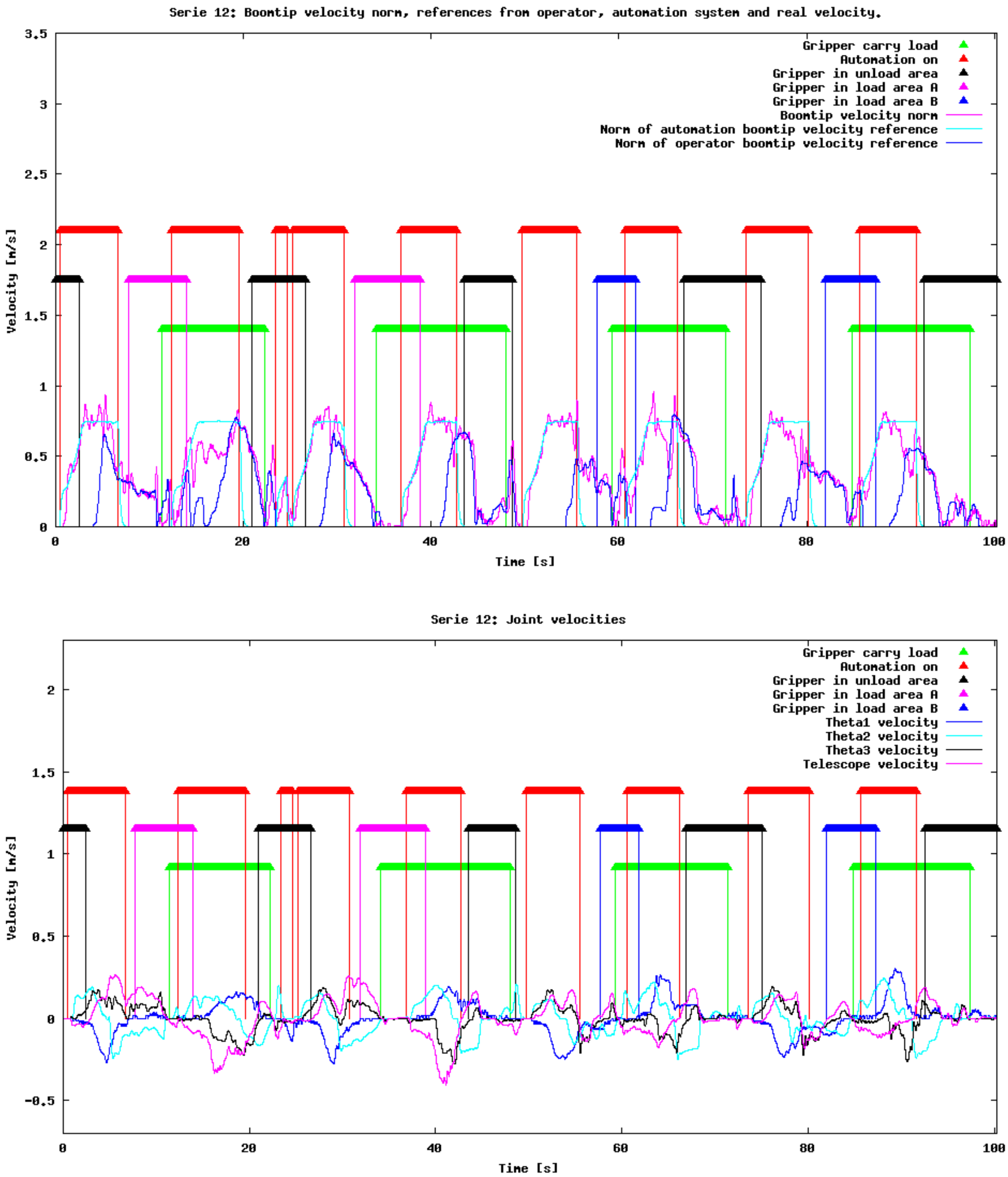
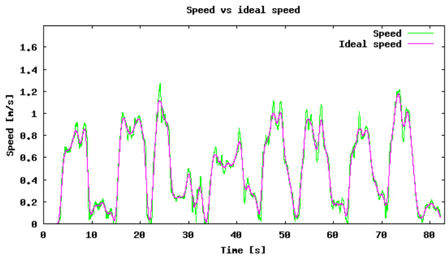
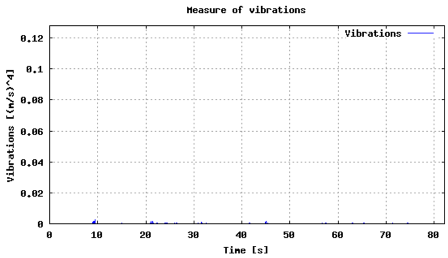


Figure 44: Operator 2 , serie 12 – Boom–tip velocity, and joint velocities versus time, *shared control* with boom–tip control

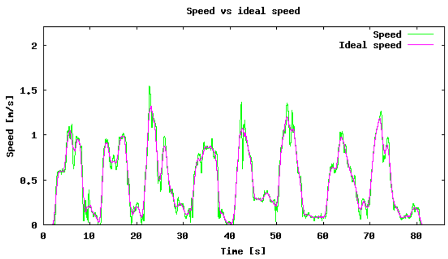
B.2.2 Boom–tip vibrations



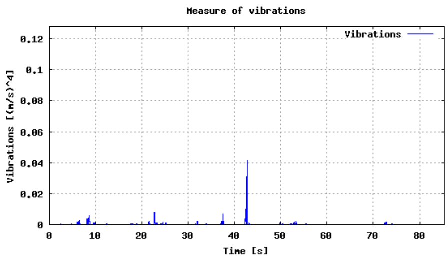
(a) Serie 1 – Ideal speed vs actual speed.



(b) Serie 1 – Vibrations.

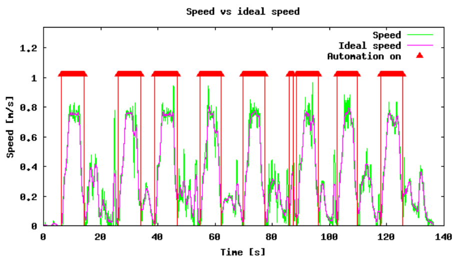


(c) Serie 2 – Ideal speed vs actual speed.

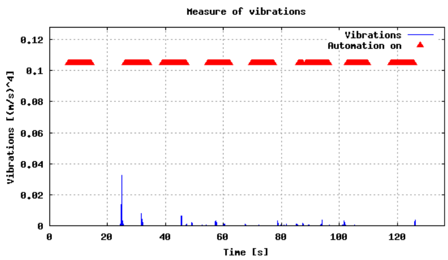


(d) Serie 2 – Vibrations.

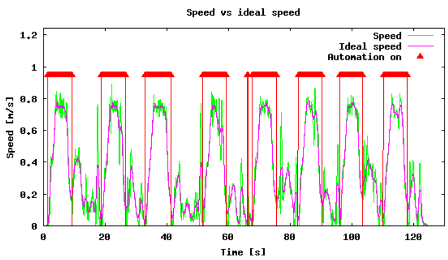
Figure 45: Operator 2 – Manual joint control



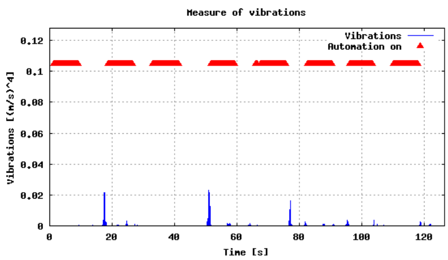
(a) Serie 3 – Ideal speed vs actual speed.



(b) Serie 3 – Vibrations.

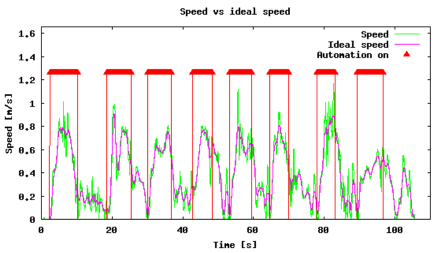


(c) Serie 4 – Ideal speed vs actual speed.

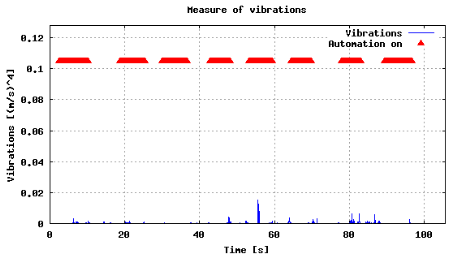


(d) Serie 4 – Vibrations.

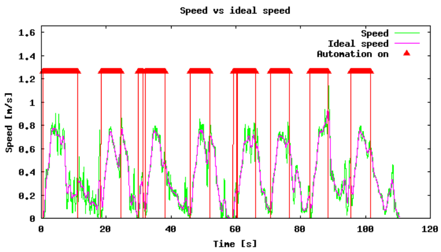
Figure 46: Operator 2 – Joint control with *traded control*.



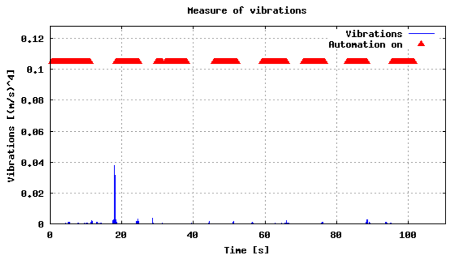
(a) Serie 5 – Ideal speed vs actual speed.



(b) Serie 5 – Vibrations.

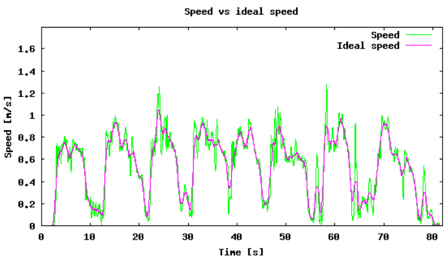


(c) Serie 6 – Ideal speed vs actual speed.

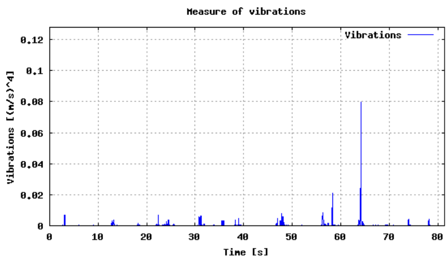


(d) Serie 6 – Vibrations.

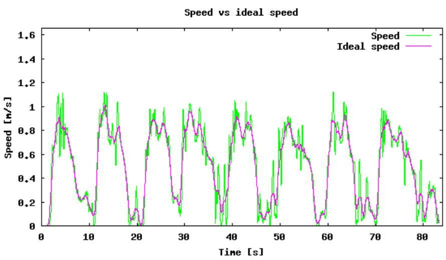
Figure 47: Operator 2 – Joint control with *shared control*.



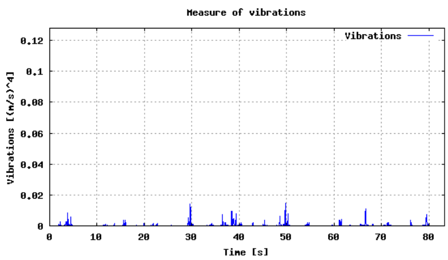
(a) Serie 7 – Ideal speed vs actual speed.



(b) Serie 7 – Vibrations.

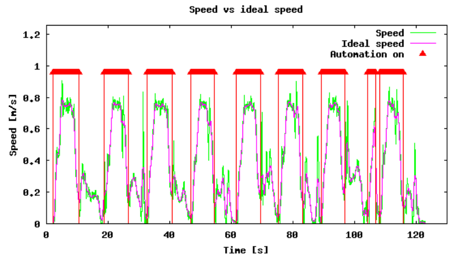


(c) Serie 8 – Ideal speed vs actual speed.

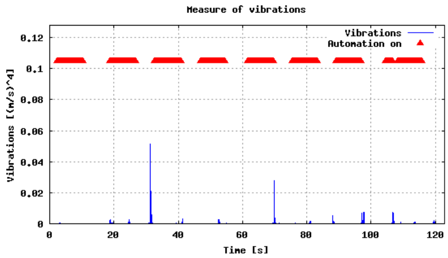


(d) Serie 8 – Vibrations.

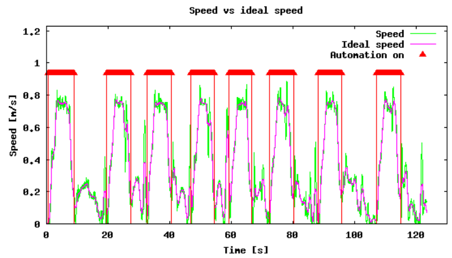
Figure 48: Operator 2 – Manual boom–tip control.



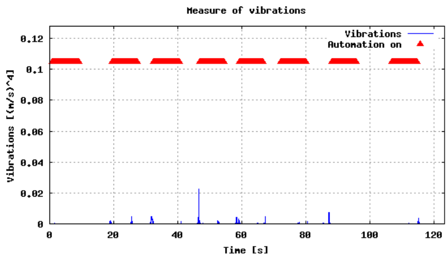
(a) Serie 9 – Ideal speed vs actual speed.



(b) Serie 9 – Vibrations.

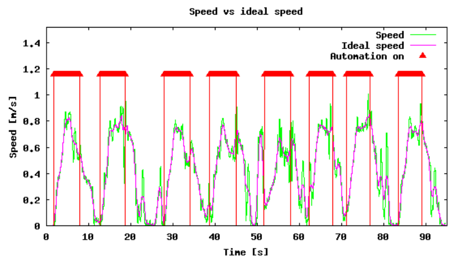


(c) Serie 10 – Ideal speed vs actual speed.

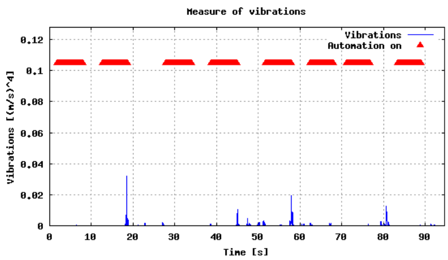


(d) Serie 10 – Vibrations.

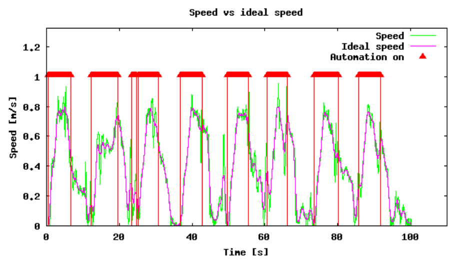
Figure 49: Operator 2 – Boom–tip control with *traded control*.



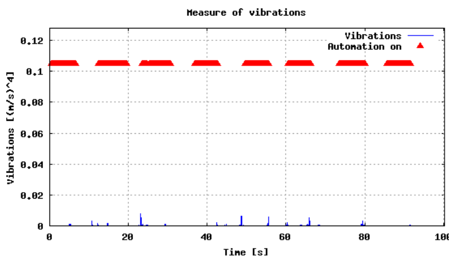
(a) Serie 11 – Ideal speed vs actual speed.



(b) Serie 11 – Vibrations.



(c) Serie 12 – Ideal speed vs actual speed.



(d) Serie 12 – Vibrations.

Figure 50: Operator 2 – Boom–tip control with *shared control*.

B.3 Operator 3

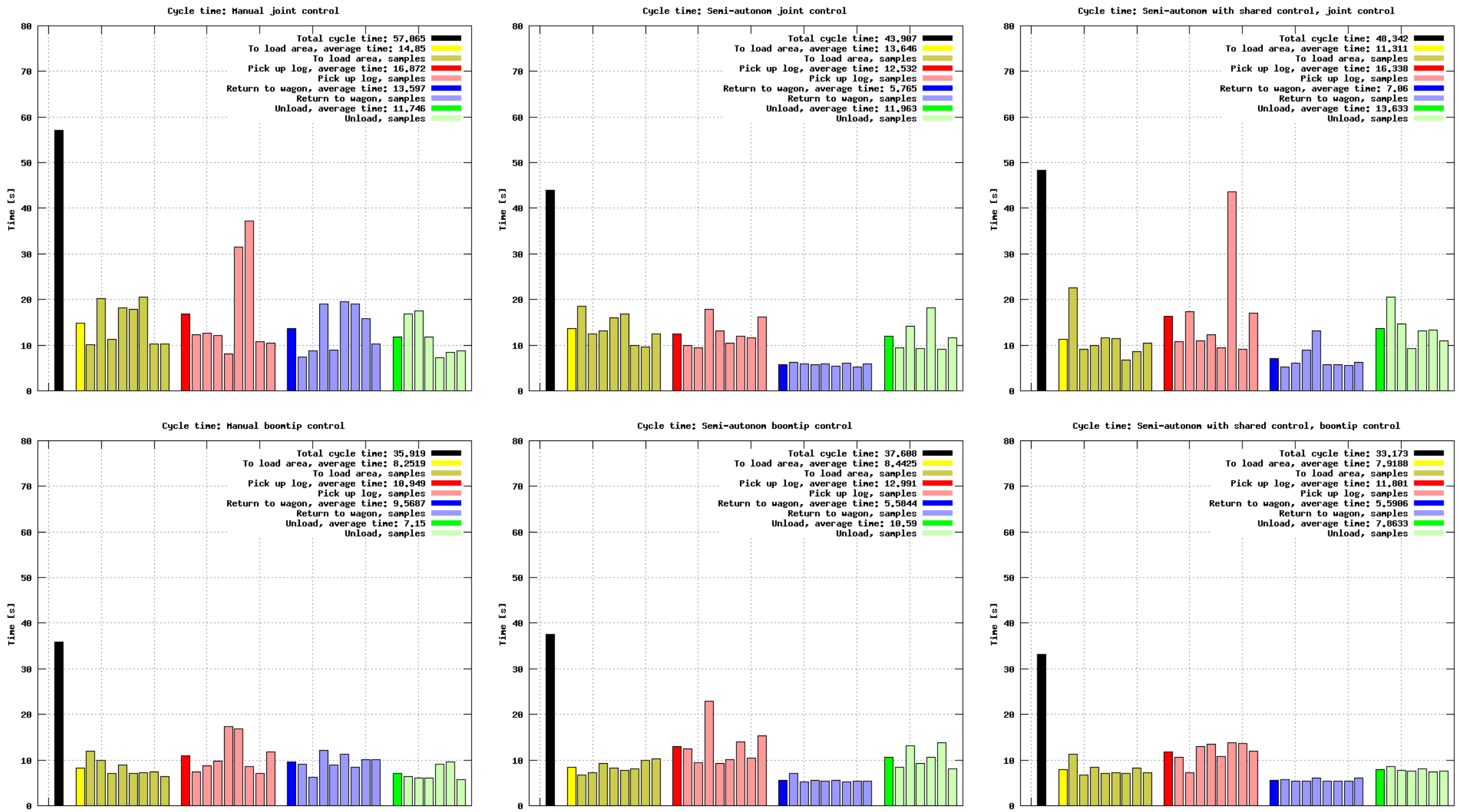
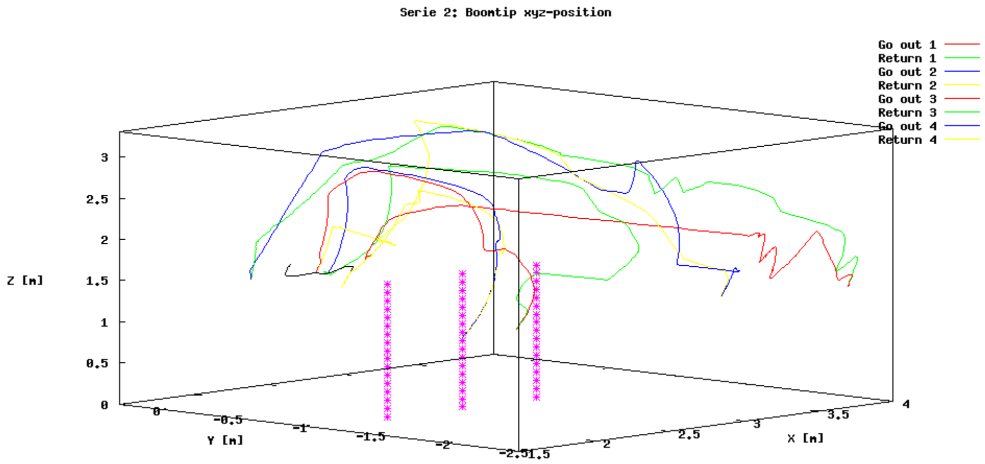
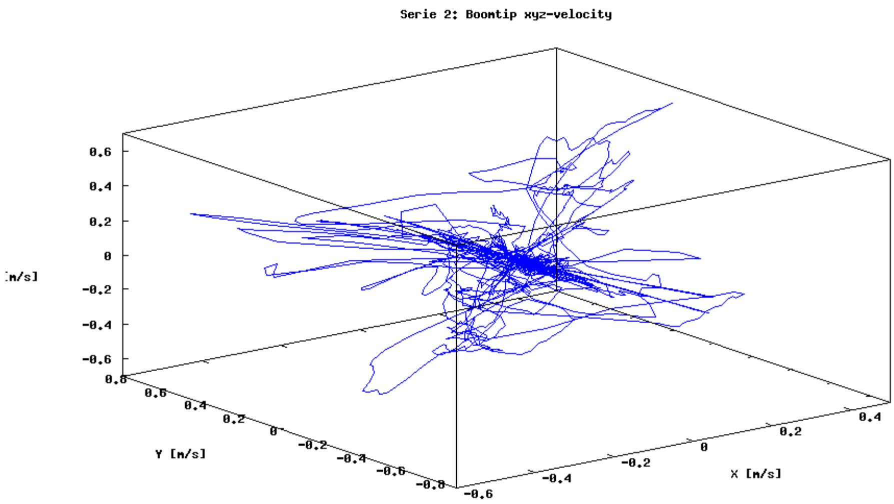


Figure 51: Operator 3 summary

B.3.1 Samples

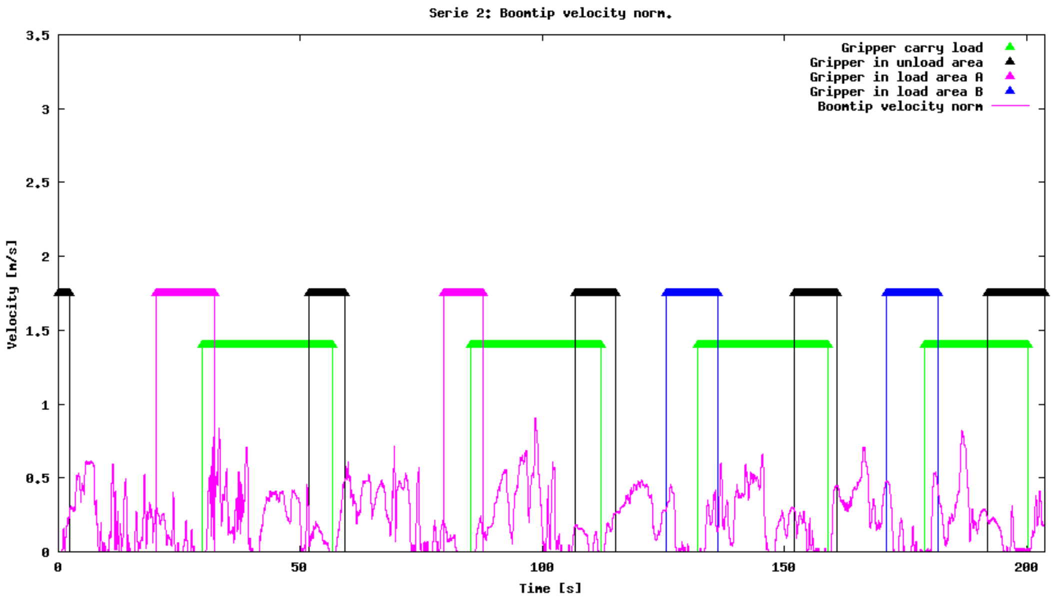


(a) Operator 3 , serie 2 – Boom–tip position, manual joint control.



(b) Operator 3 , serie 2 – Boom–tip velocity, manual joint control.

Figure 52



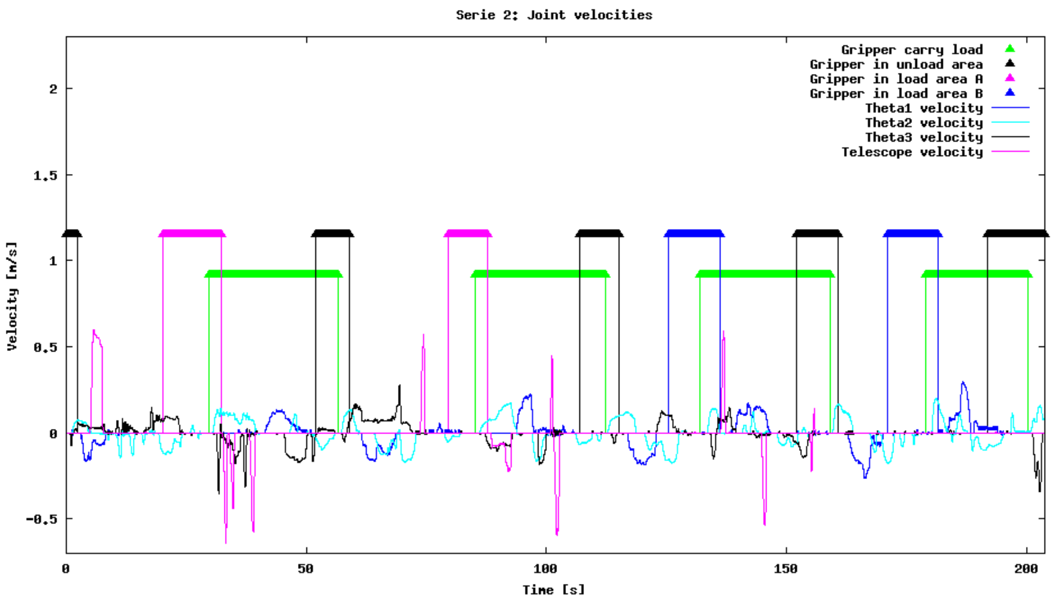
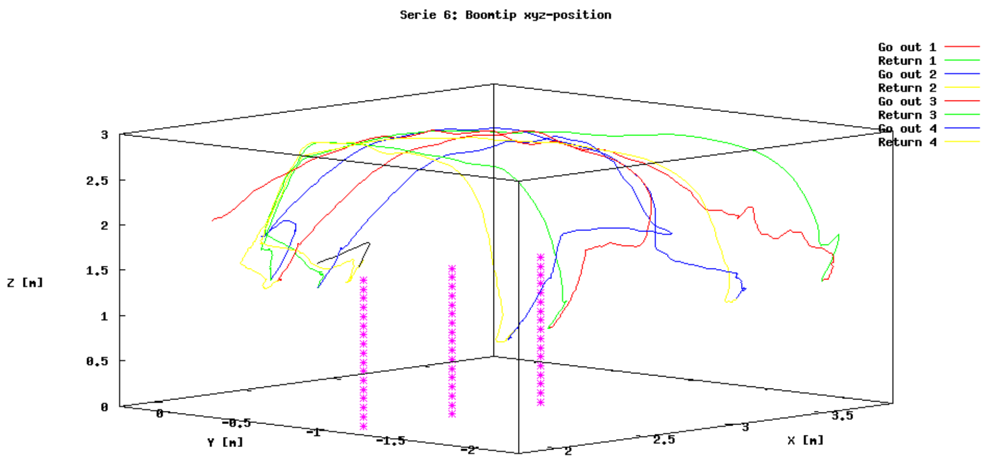
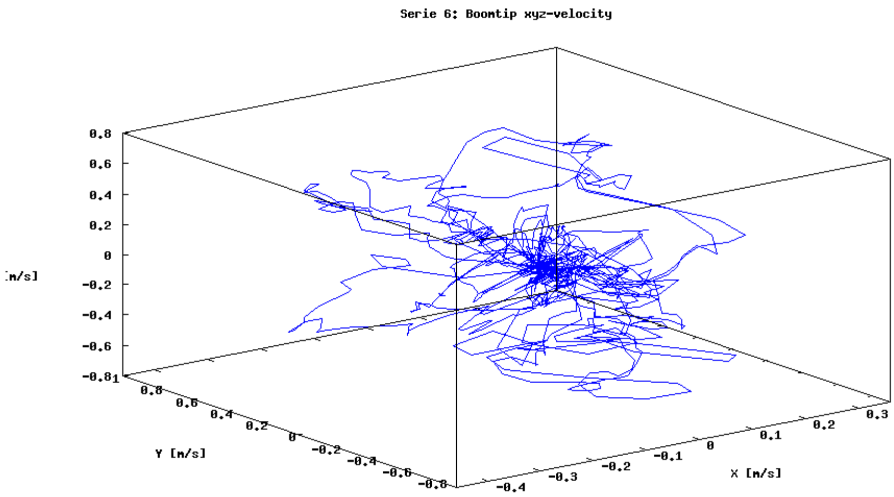


Figure 53: Operator 3 , serie 2 – Boom–tip velocity, boom–tip velocity and joint velocities versus time, manual joint control

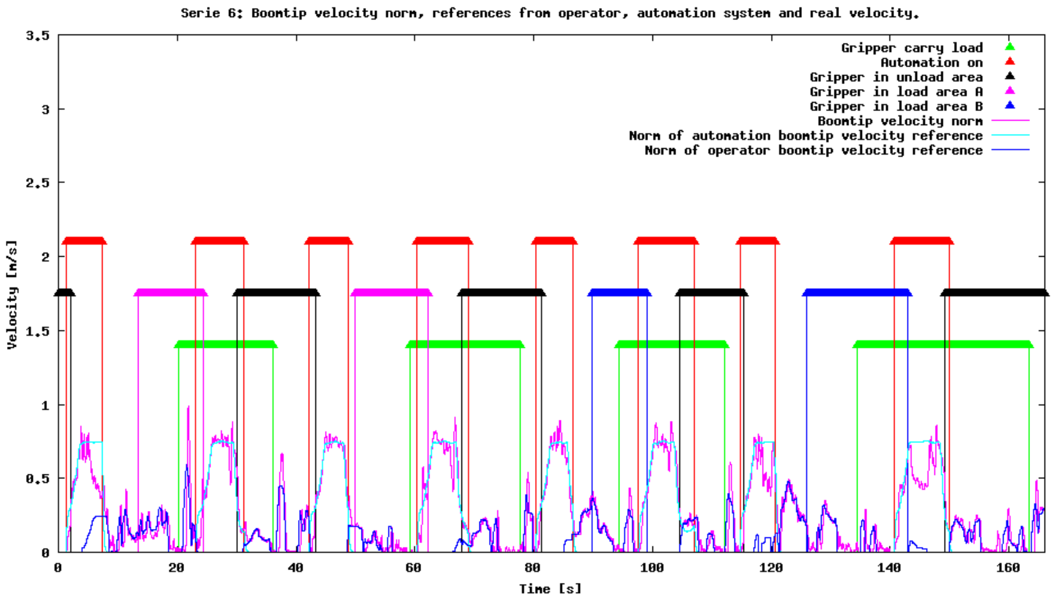


(a) Operator 3 , serie 6 – Boom–tip position, *traded control* with joint control.



(b) Operator 3 , serie 6 – Boom–tip velocity, *traded control* with joint control.

Figure 54



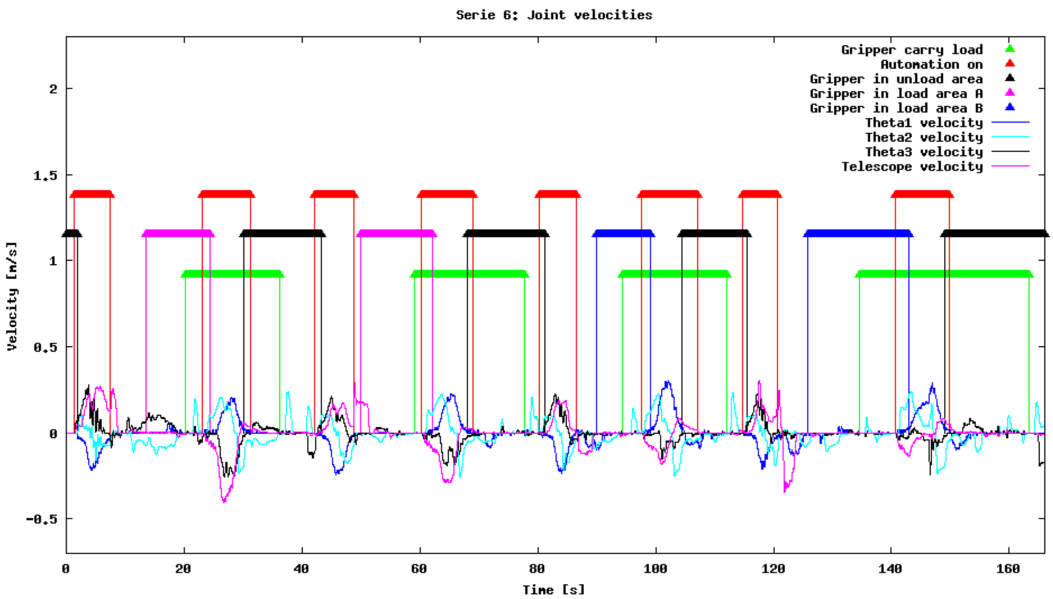
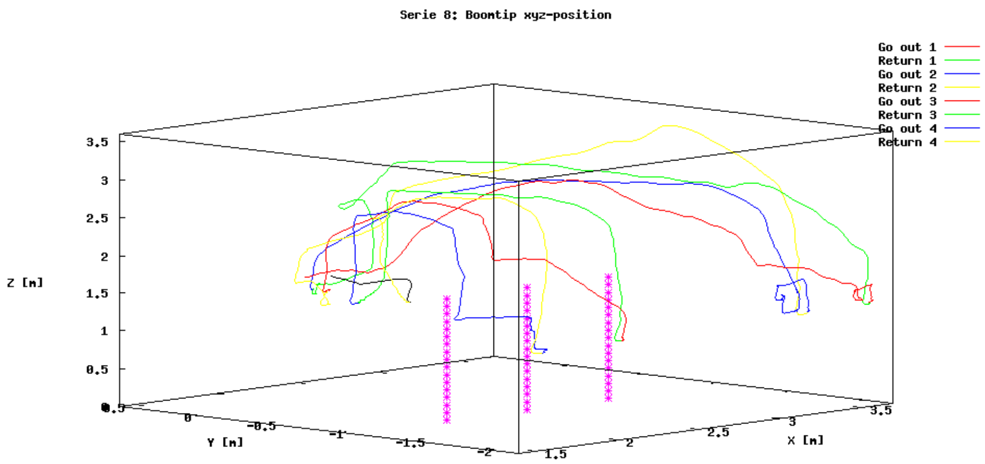
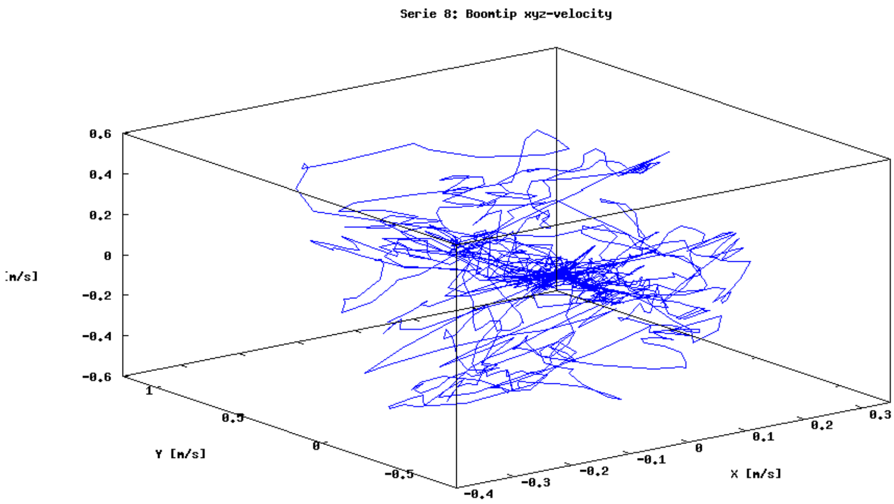


Figure 55: Operator 3 , serie 6 – Boom–tip velocity, boom–tip velocity and joint velocities versus time, *traded control* with joint control

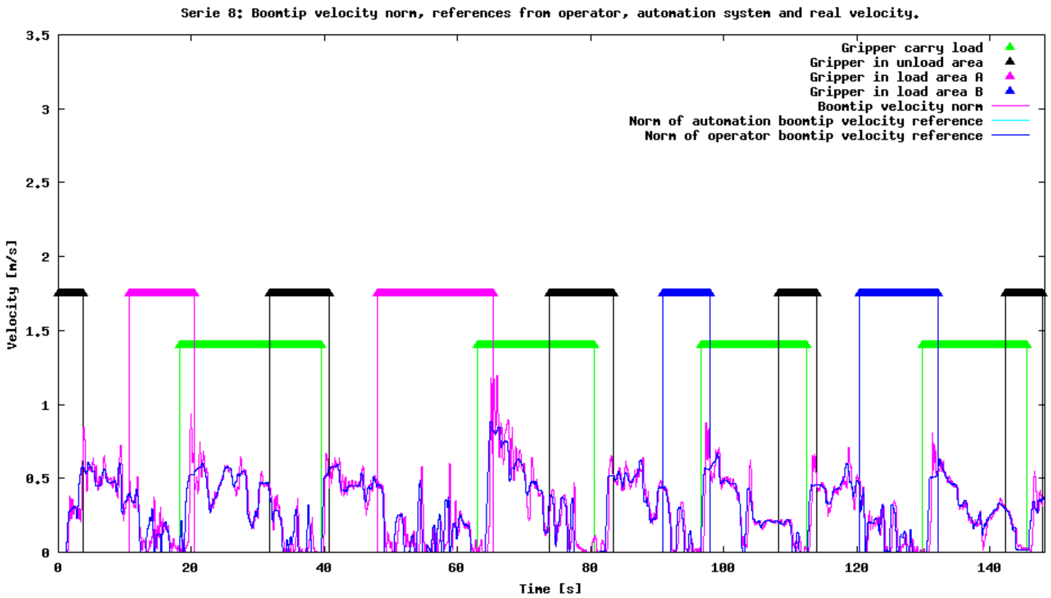


(a) Operator 3 , serie 8 – Boom–tip position, manual boom–tip control.



(b) Operator 3 , serie 8 – Boom–tip velocity, manual boom–tip control.

Figure 56



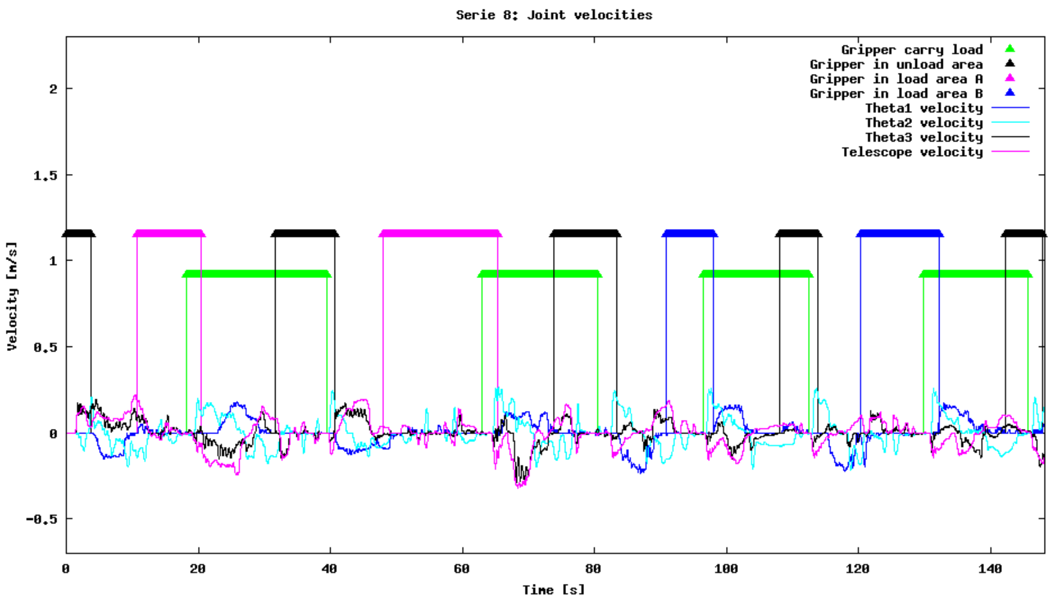
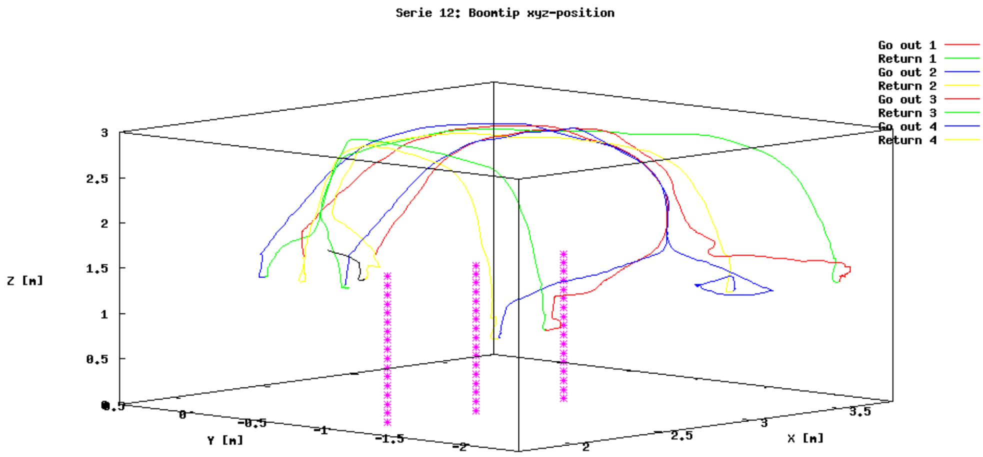
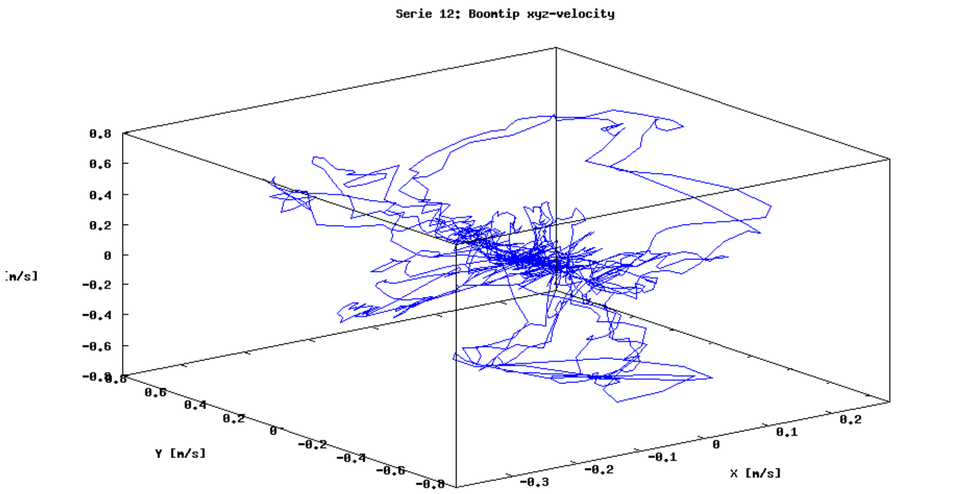


Figure 57: Operator 3 , serie 8 – Boom–tip velocity, boom–tip velocity and joint velocities versus time, manual boom–tip control



(a) Operator 3 , serie 12 – Boom–tip position, *shared control* with boom–tip control.



(b) Operator 3 , serie 12 – Boom–tip velocity, *shared control* with boom–tip control.

Figure 58

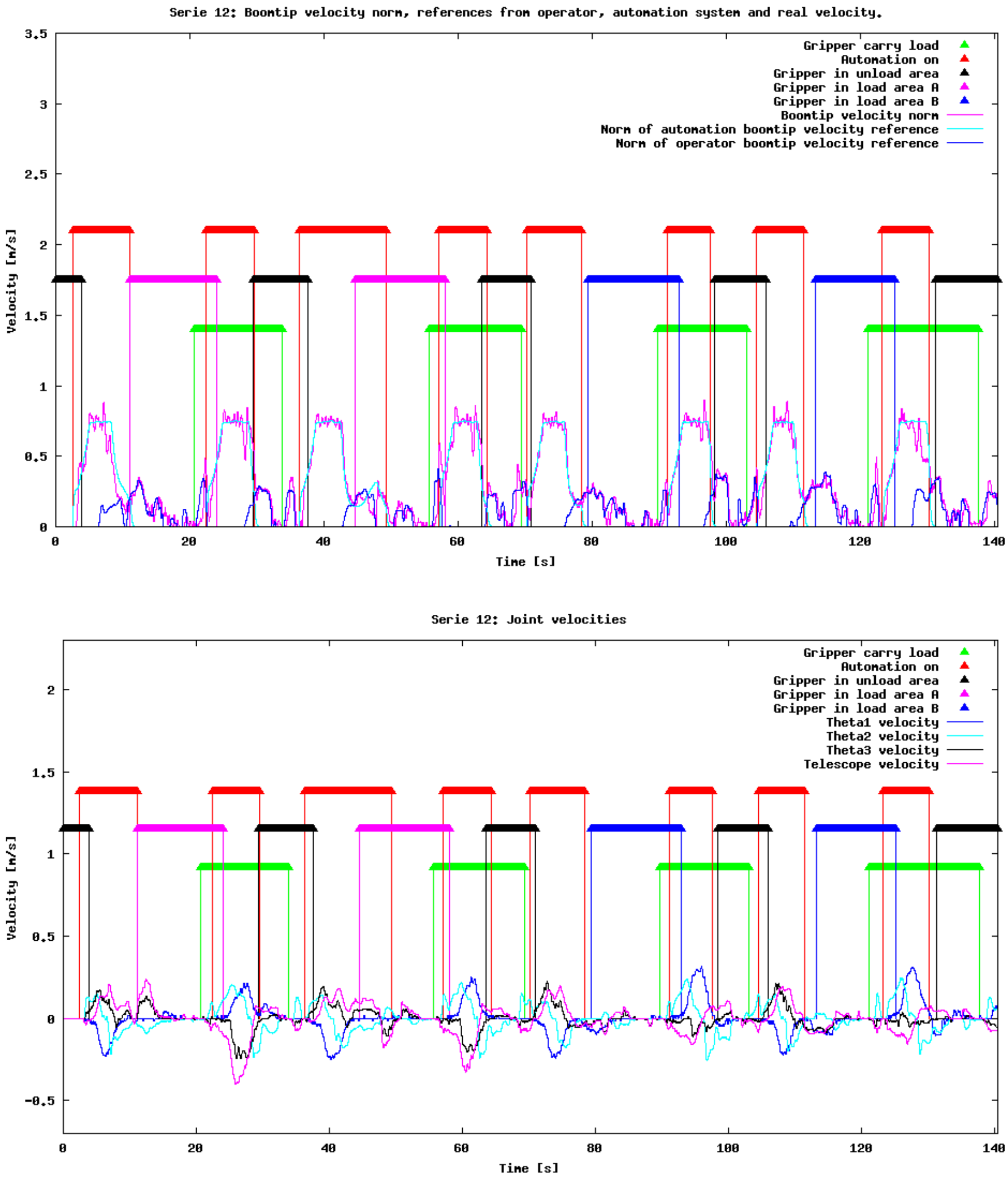
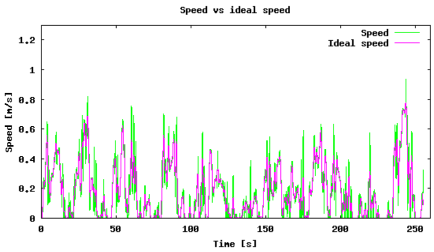
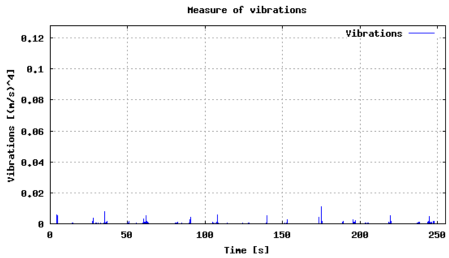


Figure 59: Operator 3 , serie 12 – Boom–tip velocity, boom–tip velocity and joint velocities versus time, *shared control* with boom–tip control

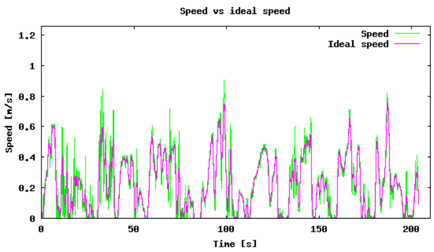
B.3.2 Boom–tip vibrations



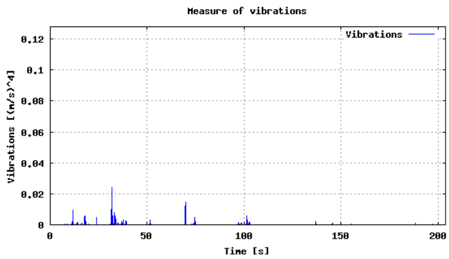
(a) Serie 1 – Ideal speed vs actual speed.



(b) Serie 1 – Vibrations.

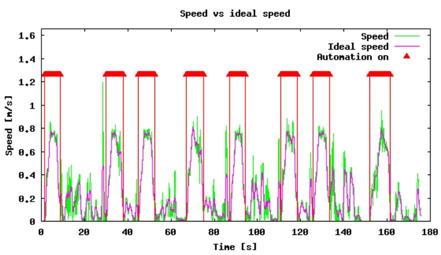


(c) Serie 2 – Ideal speed vs actual speed.

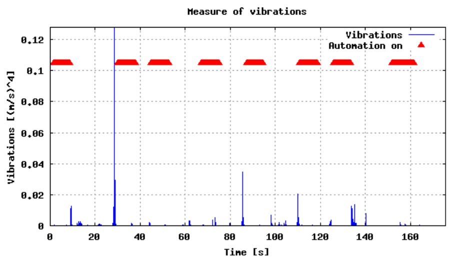


(d) Serie 2 – Vibrations.

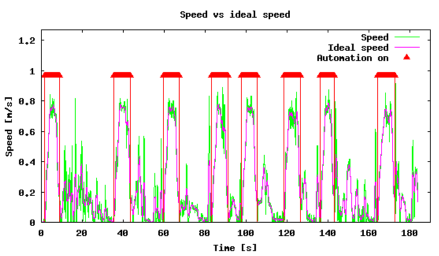
Figure 60: Operator 3 – Manual joint control



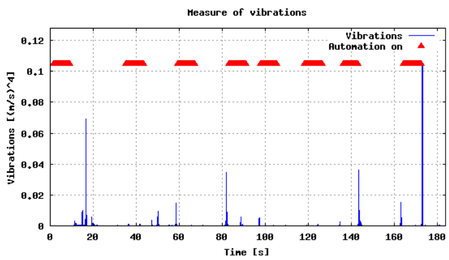
(a) Serie 3 – Ideal speed vs actual speed.



(b) Serie 3 – Vibrations.

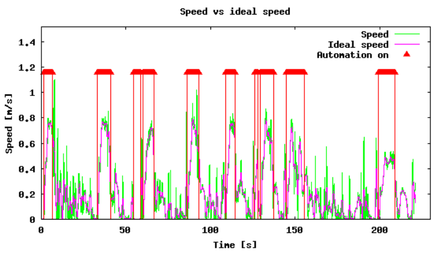


(c) Serie 4 – Ideal speed vs actual speed.

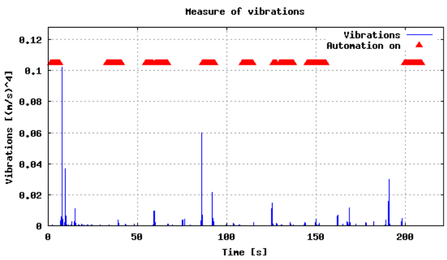


(d) Serie 4 – Vibrations.

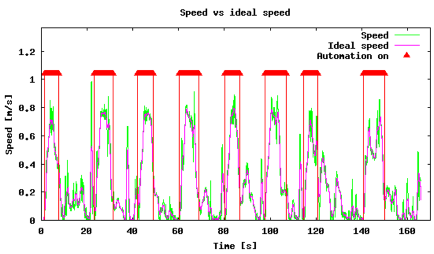
Figure 61: Operator 3 – Joint control with *traded control*.



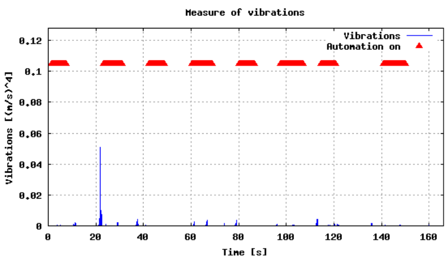
(a) Serie 5 – Ideal speed vs actual speed.



(b) Serie 5 – Vibrations.

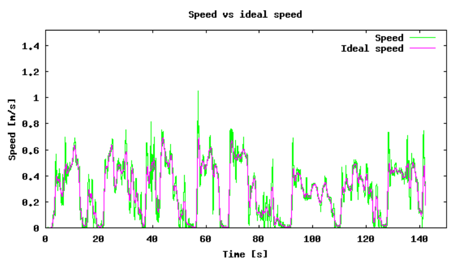


(c) Serie 6 – Ideal speed vs actual speed.

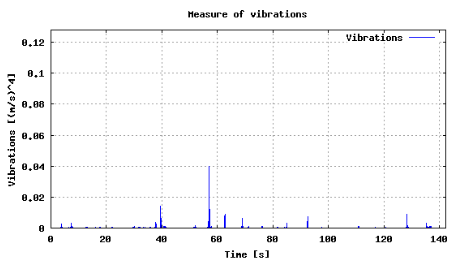


(d) Serie 6 – Vibrations.

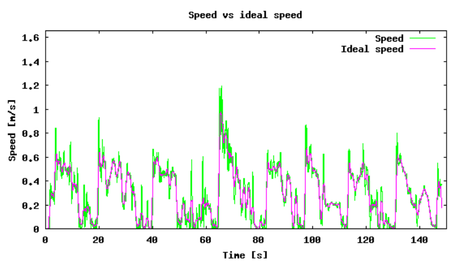
Figure 62: Operator 3 – Joint control with *shared control*.



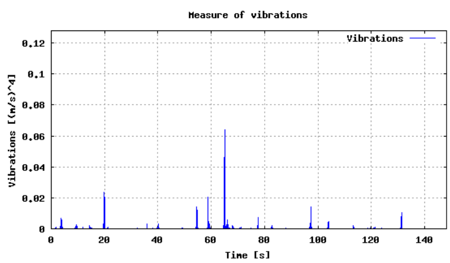
(a) Serie 7 – Ideal speed vs actual speed.



(b) Serie 7 – Vibrations.

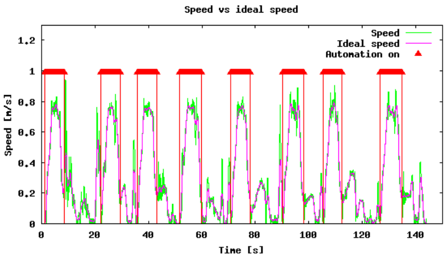


(c) Serie 8 – Ideal speed vs actual speed.

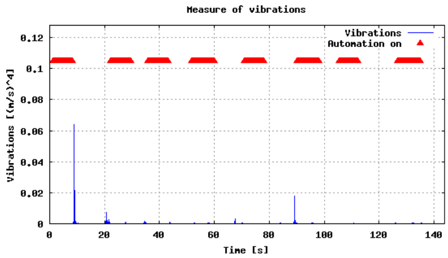


(d) Serie 8 – Vibrations.

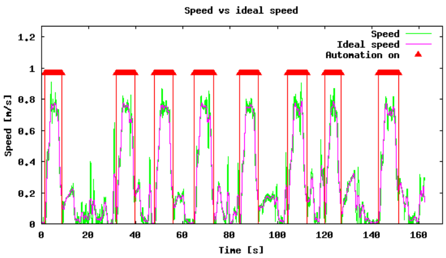
Figure 63: Operator 3 – Manual boom–tip control.



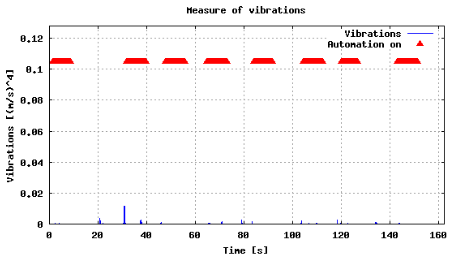
(a) Serie 9 – Ideal speed vs actual speed.



(b) Serie 9 – Vibrations.

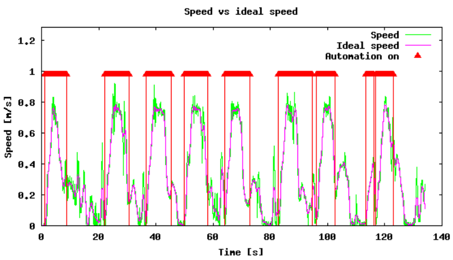


(c) Serie 10 – Ideal speed vs actual speed.

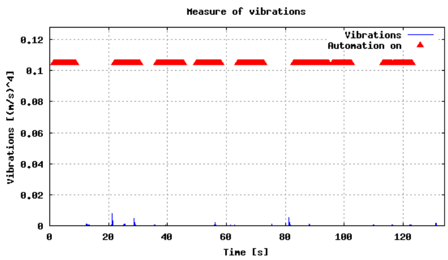


(d) Serie 10 – Vibrations.

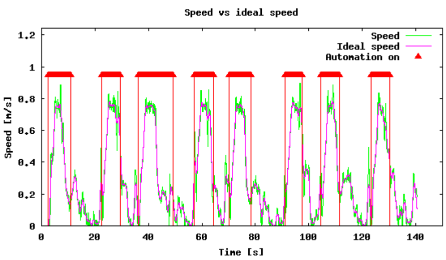
Figure 64: Operator 3 – Boom–tip control with *traded control*.



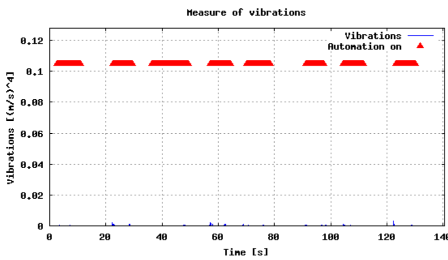
(a) Serie 11 – Ideal speed vs actual speed.



(b) Serie 11 – Vibrations.



(c) Serie 12 – Ideal speed vs actual speed.



(d) Serie 12 – Vibrations.

Figure 65: Operator 3 – Boom–tip control with *shared control*.

B.4 Operator 4

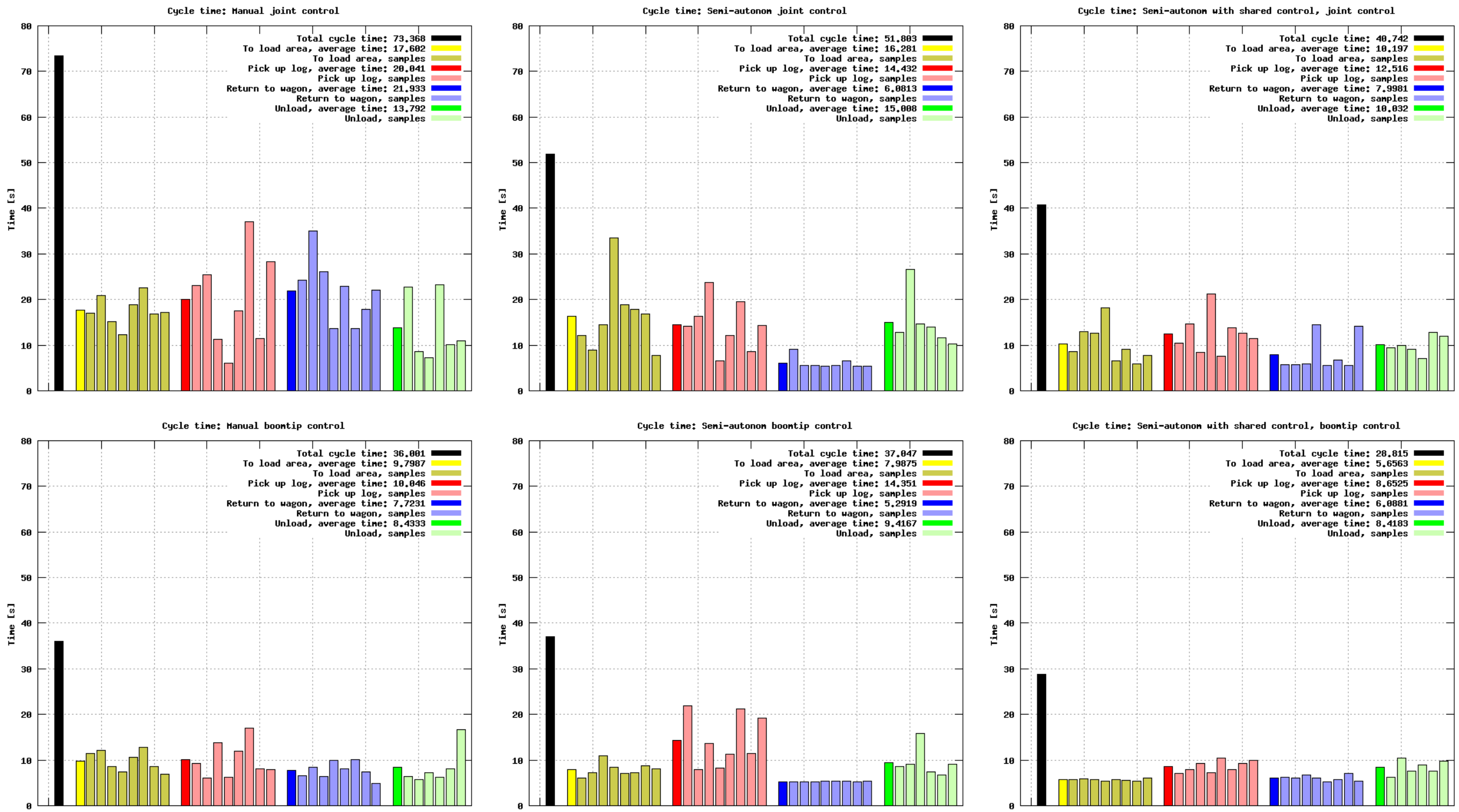
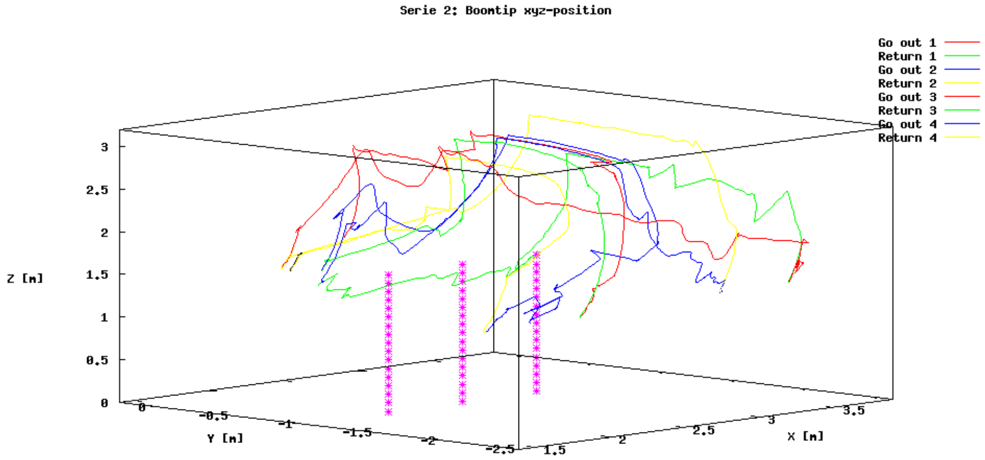
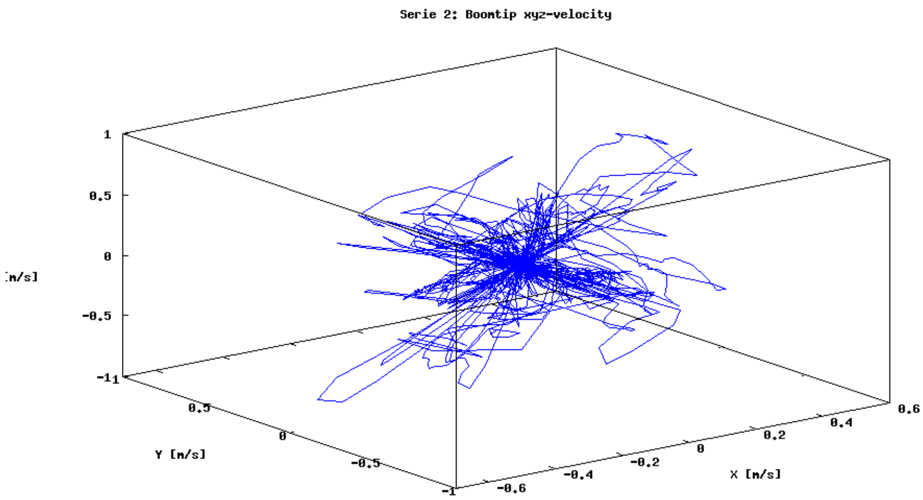


Figure 66: Operator 4 summary

B.4.1 Samples



(a) Operator 4 , serie 2 – Boom–tip position, manual joint control.



(b) Operator 4 , serie 2 – Boom–tip velocity, manual joint control.

Figure 67

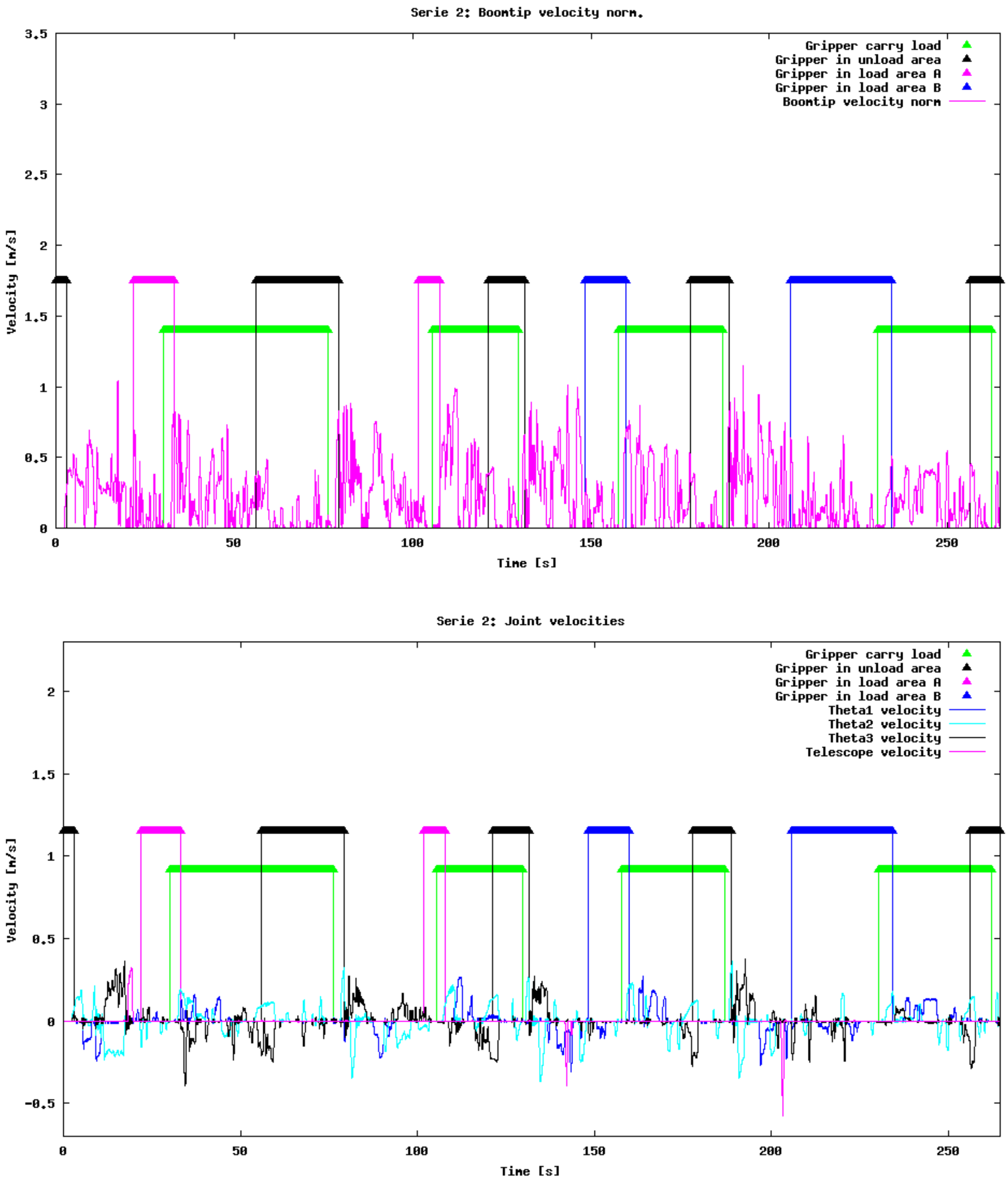
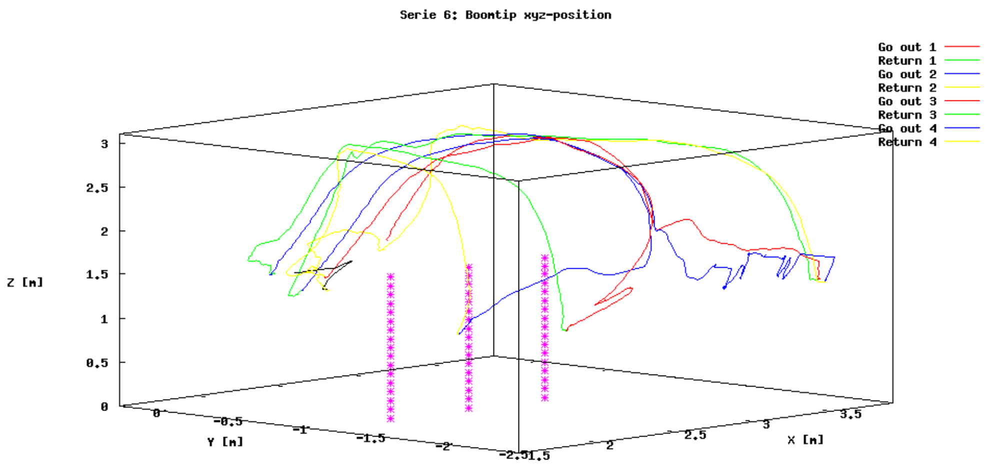
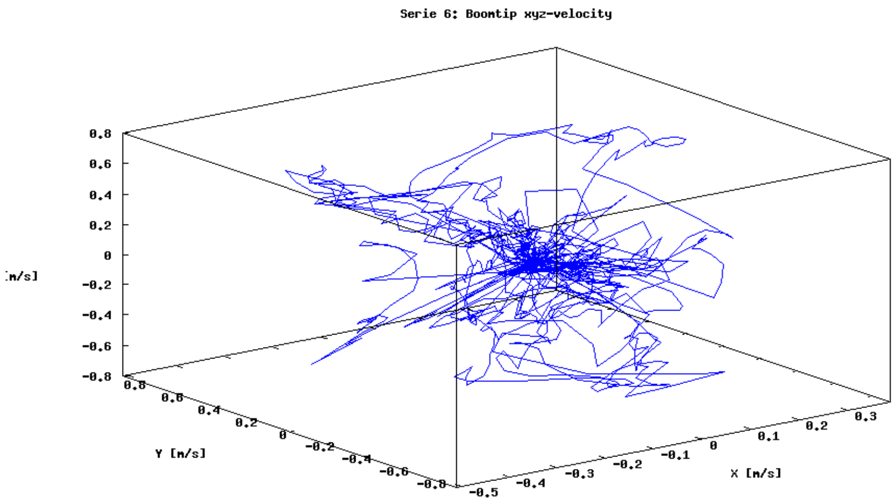


Figure 68: Operator 4 , serie 2 – Boom–tip velocity, boom–tip velocity and joint velocities versus time, manual joint control

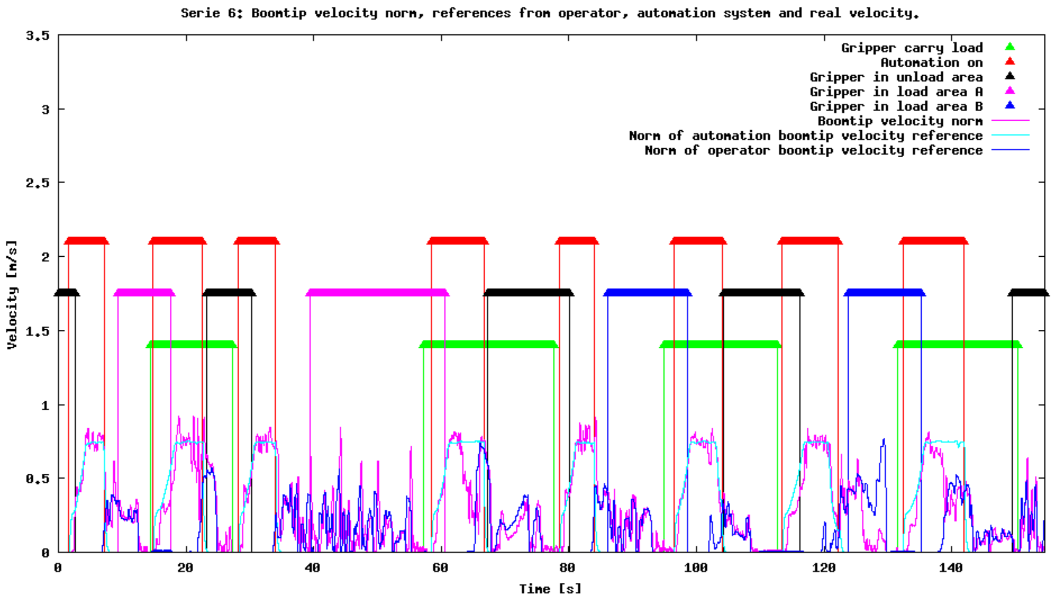


(a) Operator 4 , serie 6 – Boom–tip position, *traded control* with joint control.



(b) Operator 4 , serie 6 – Boom–tip velocity, *traded control* with joint control.

Figure 69



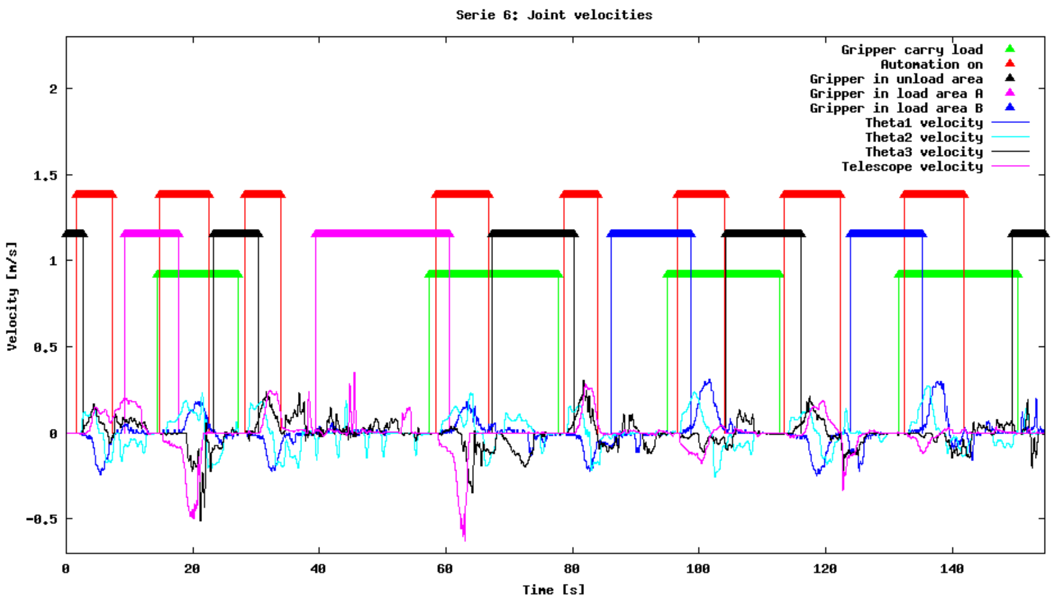
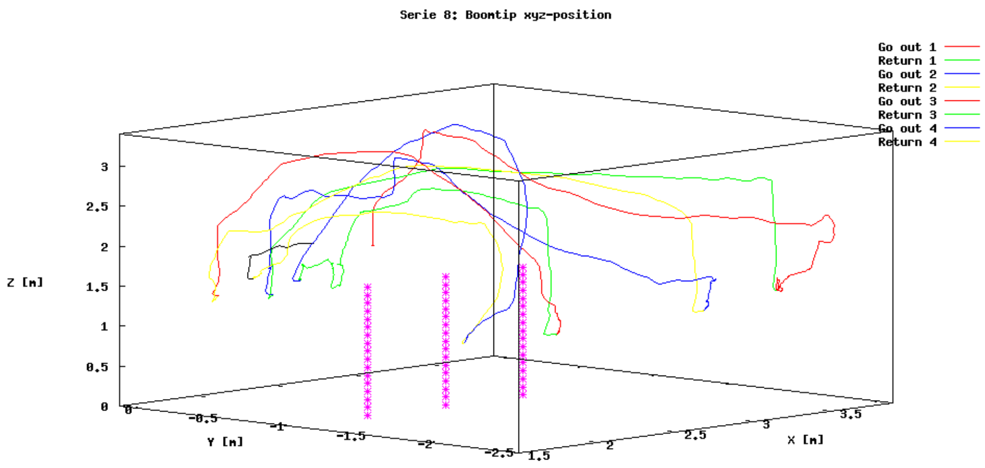
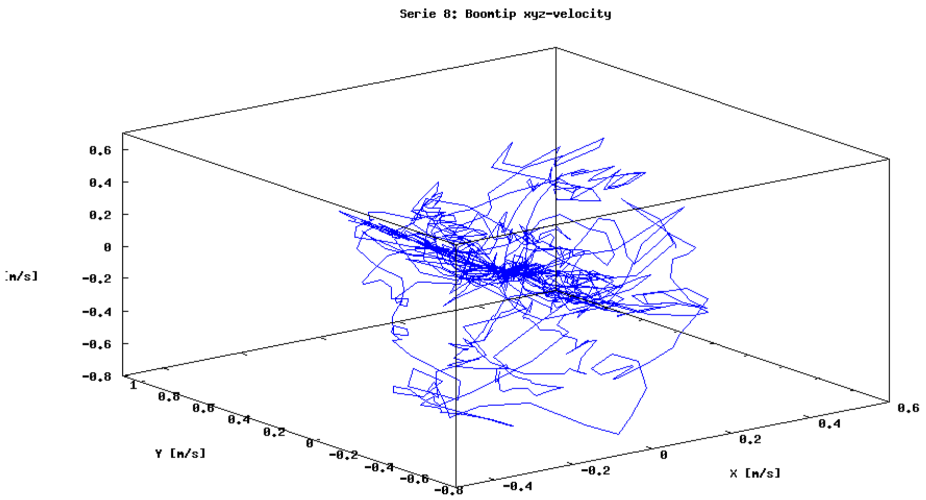


Figure 70: Operator 4 , serie 6 – Boom–tip velocity, boom–tip velocity and joint velocities versus time, *traded control* with joint control

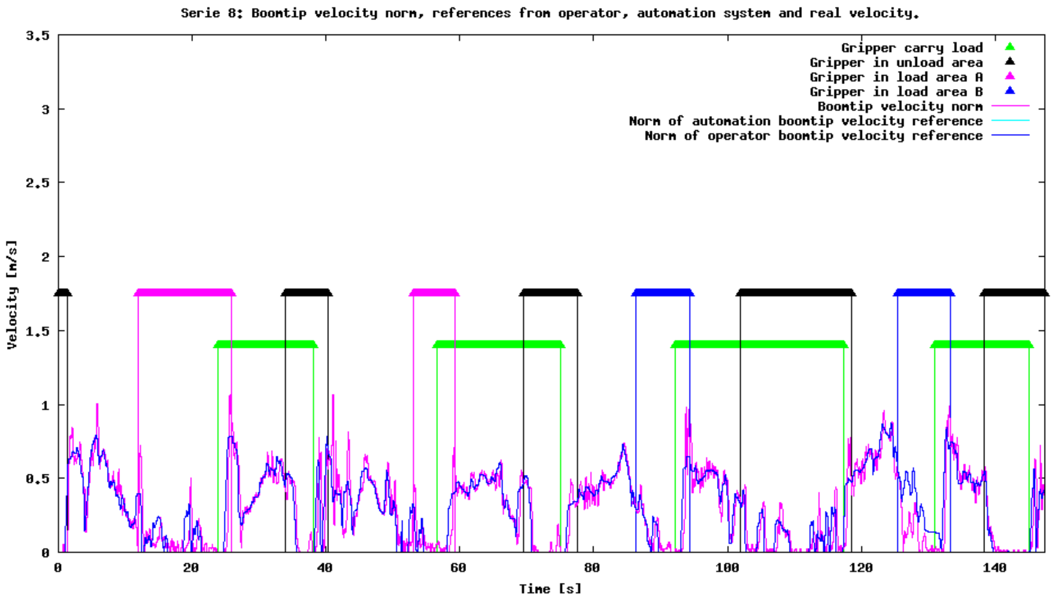


(a) Operator 4 , serie 8 – Boom–tip position, manual boom–tip control.



(b) Operator 4 , serie 8 – Boom–tip velocity, manual boom–tip control.

Figure 71



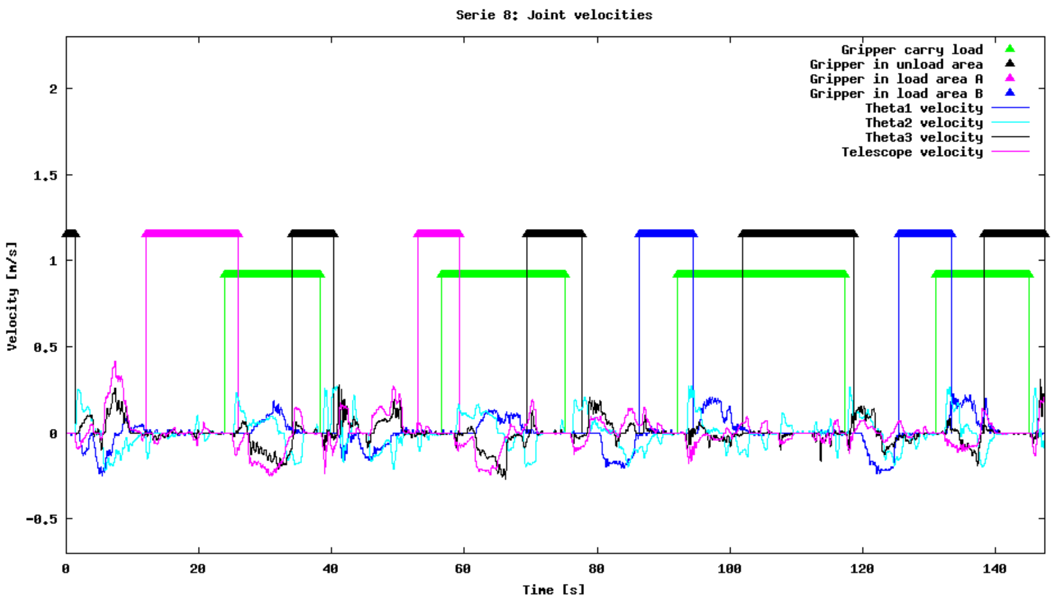
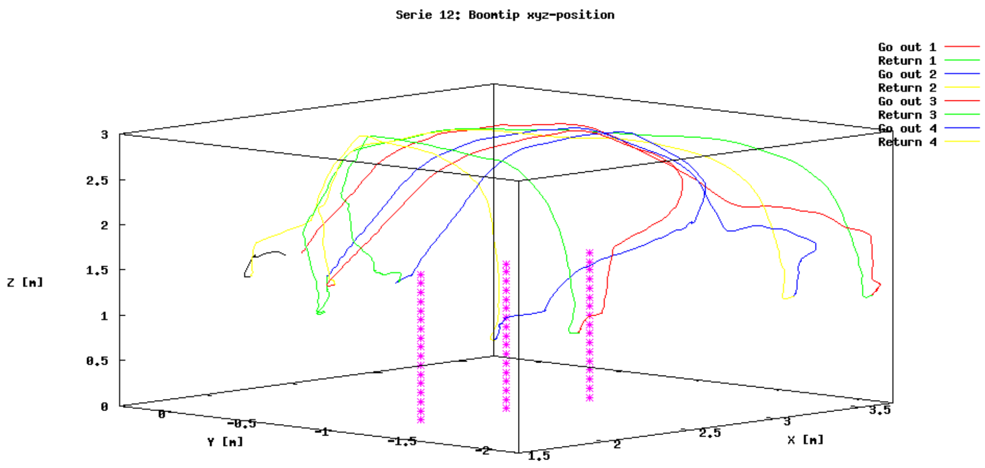
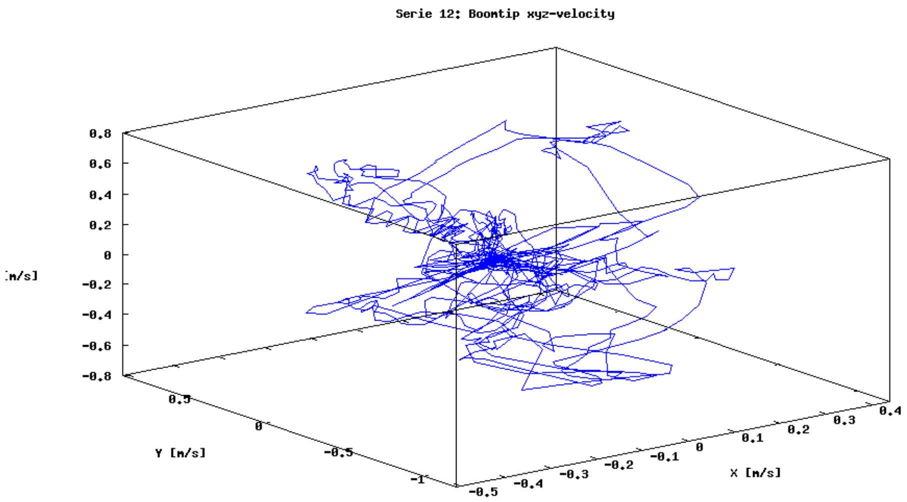


Figure 72: Operator 4 , serie 8 – Boom–tip velocity, boom–tip velocity and joint velocities versus time, manual boom–tip control

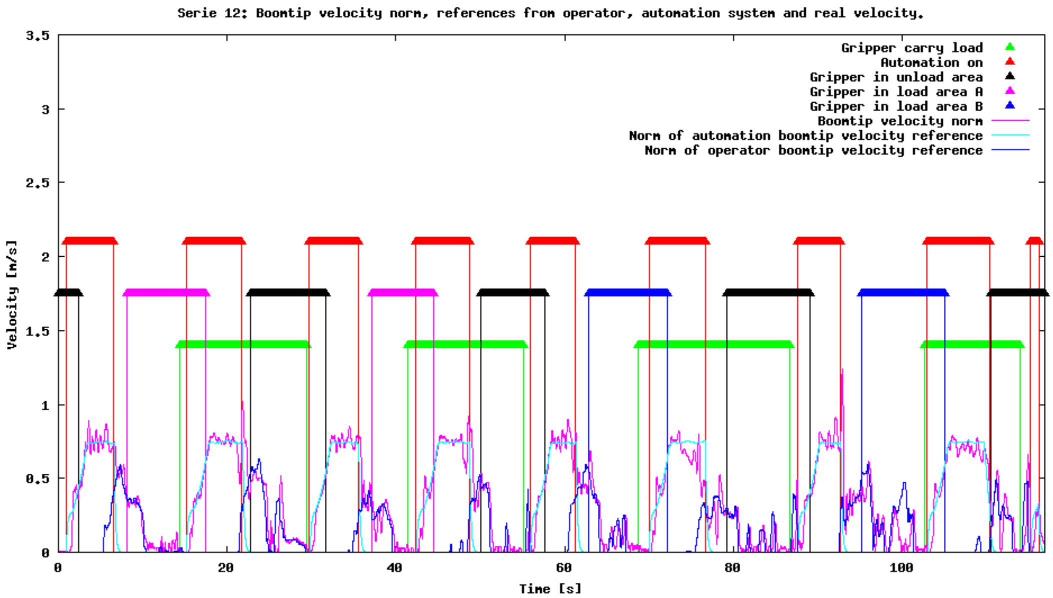


(a) Operator 4 , serie 12 – Boom–tip position, *shared control* with boom–tip control.



(b) Operator 4 , serie 12 – Boom–tip velocity, *shared control* with boom–tip control.

Figure 73



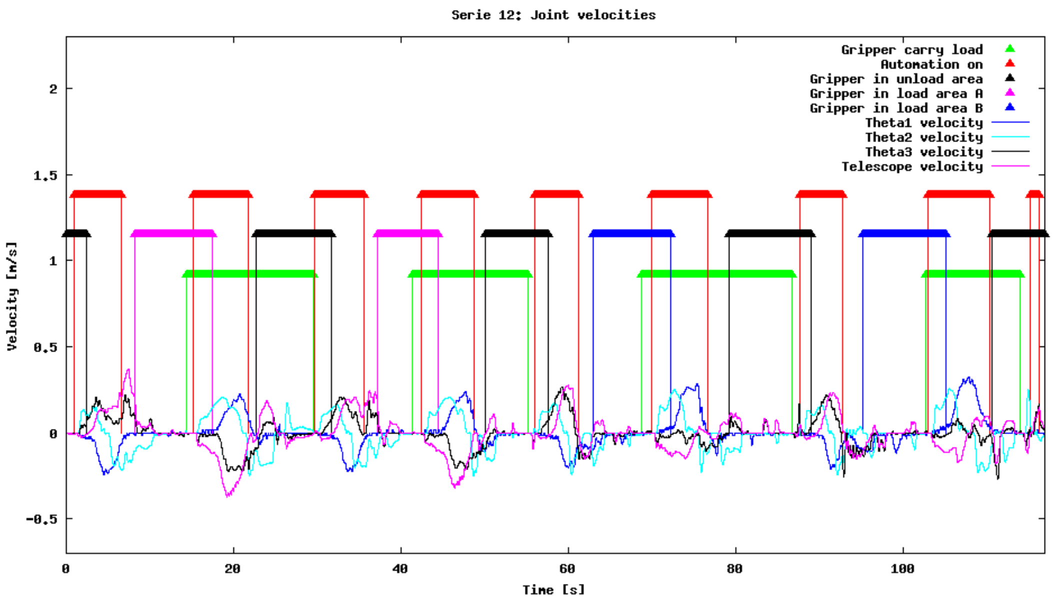
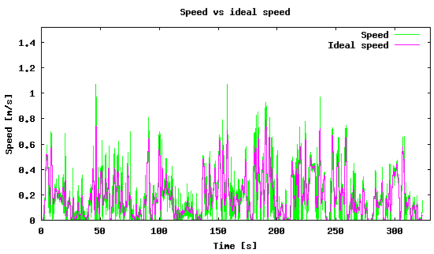
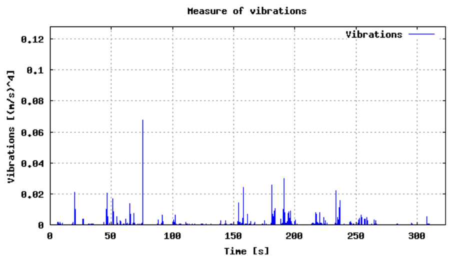


Figure 74: Operator 4 , serie 12 – Boom–tip velocity, boom–tip velocity and joint velocities versus time, *shared control* with boom–tip control

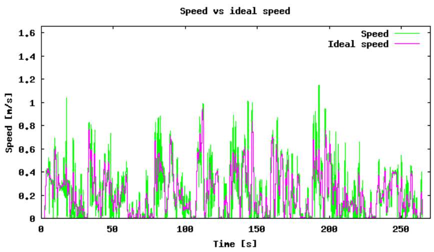
B.4.2 Boom–tip vibrations



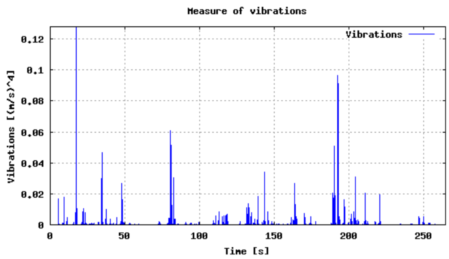
(a) Serie 1 – Ideal speed vs actual speed.



(b) Serie 1 – Vibrations.

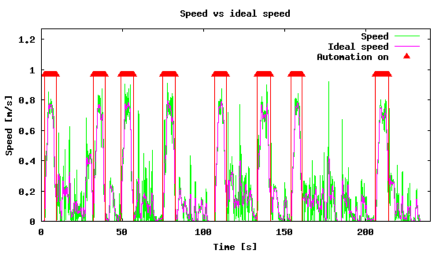


(c) Serie 2 – Ideal speed vs actual speed.

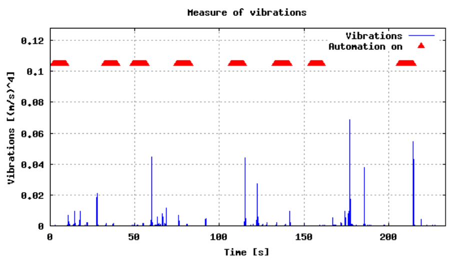


(d) Serie 2 – Vibrations.

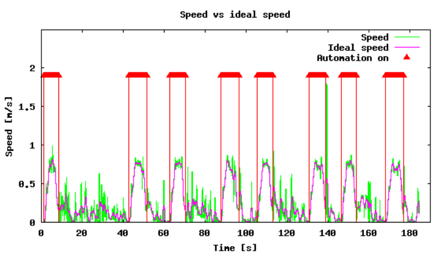
Figure 75: Operator 4 – Manual joint control



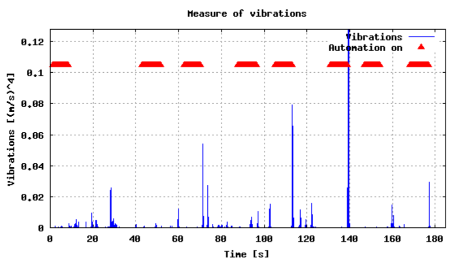
(a) Serie 3 – Ideal speed vs actual speed.



(b) Serie 3 – Vibrations.

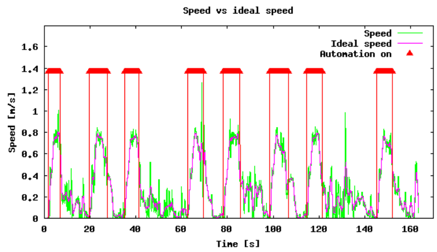


(c) Serie 4 – Ideal speed vs actual speed.

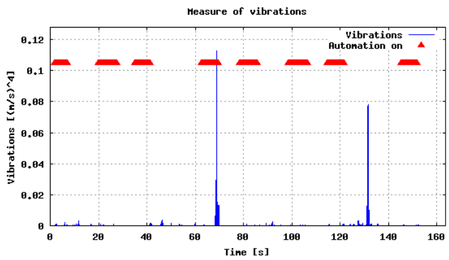


(d) Serie 4 – Vibrations.

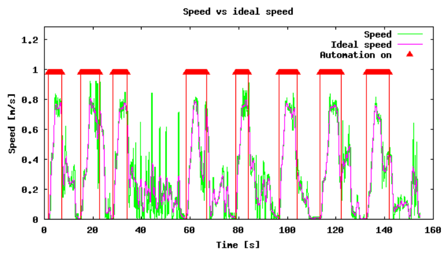
Figure 76: Operator 4 – Joint control with *traded control*.



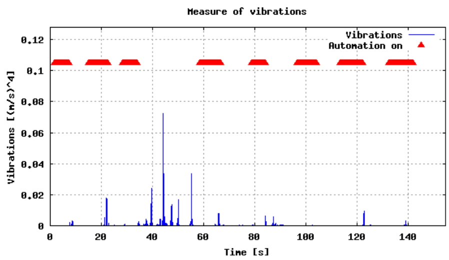
(a) Serie 5 – Ideal speed vs actual speed.



(b) Serie 5 – Vibrations.

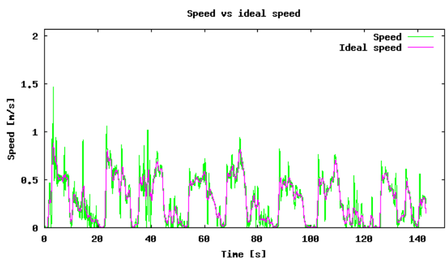


(c) Serie 6 – Ideal speed vs actual speed.

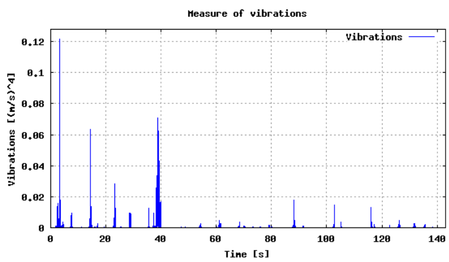


(d) Serie 6 – Vibrations.

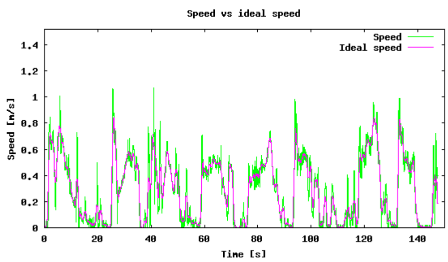
Figure 77: Operator 4 – Joint control with *shared control*.



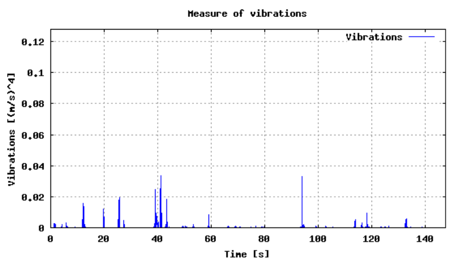
(a) Serie 7 – Ideal speed vs actual speed.



(b) Serie 7 – Vibrations.

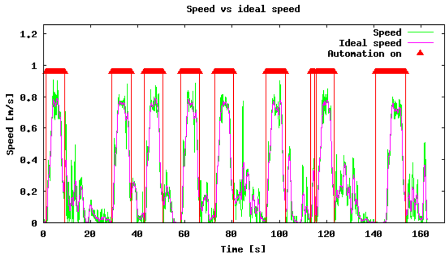


(c) Serie 8 – Ideal speed vs actual speed.

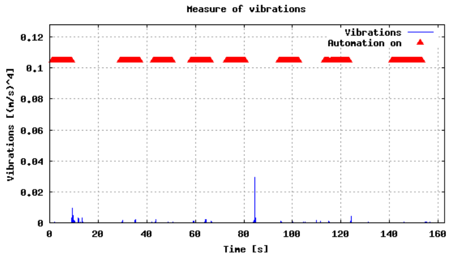


(d) Serie 8 – Vibrations.

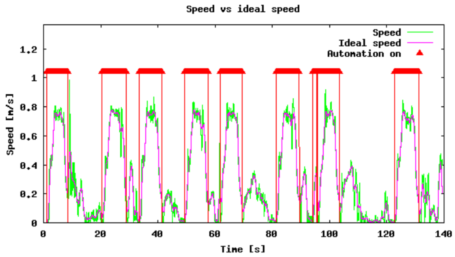
Figure 78: Operator 4 – Manual boom–tip control.



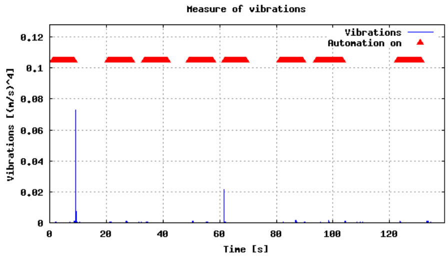
(a) Serie 9 – Ideal speed vs actual speed.



(b) Serie 9 – Vibrations.

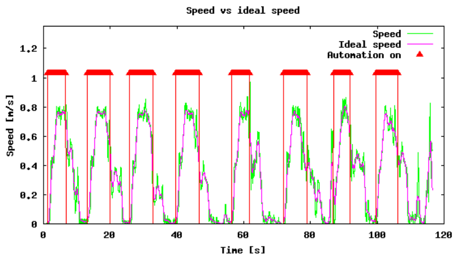


(c) Serie 10 – Ideal speed vs actual speed.

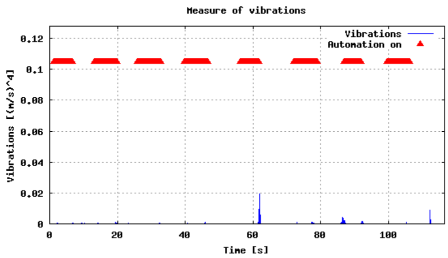


(d) Serie 10 – Vibrations.

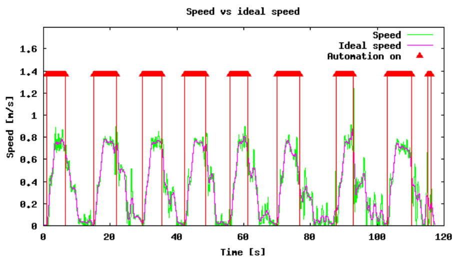
Figure 79: Operator 4 – Boom–tip control with *traded control*.



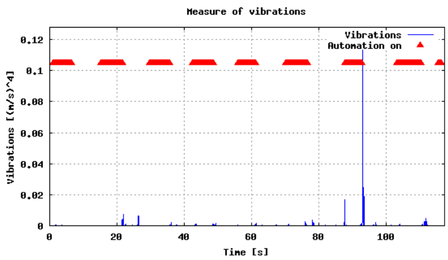
(a) Serie 11 – Ideal speed vs actual speed.



(b) Serie 11 – Vibrations.



(c) Serie 12 – Ideal speed vs actual speed.



(d) Serie 12 – Vibrations.

Figure 80: Operator 4 – Boom–tip control with *shared control*.

B.5 Operator 5

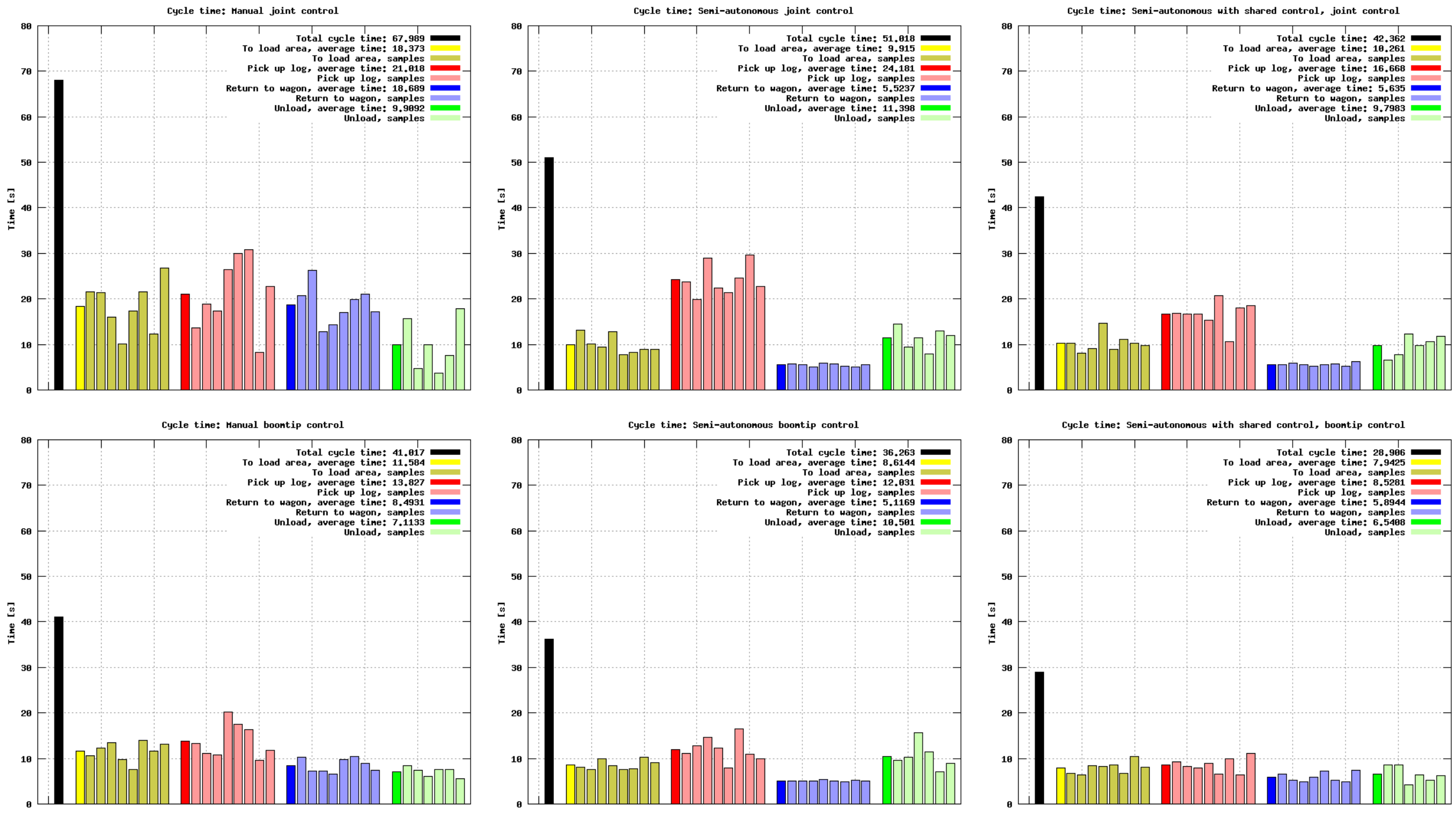
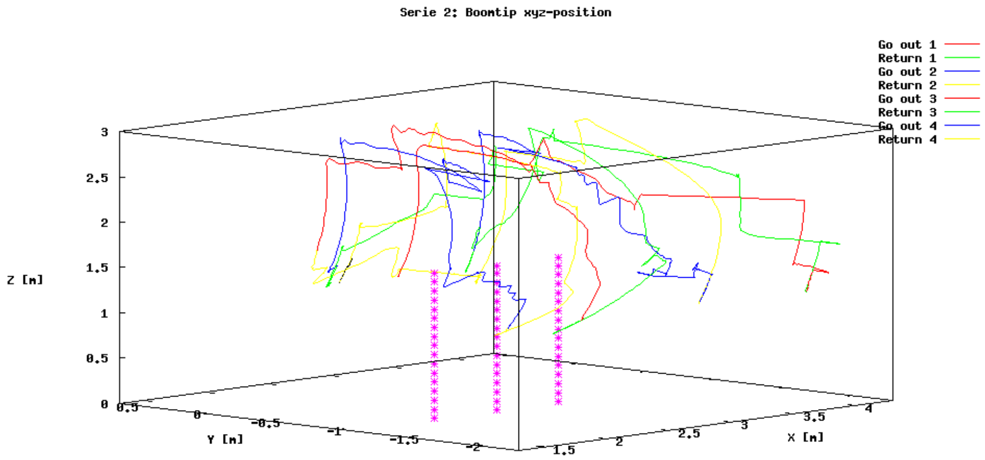
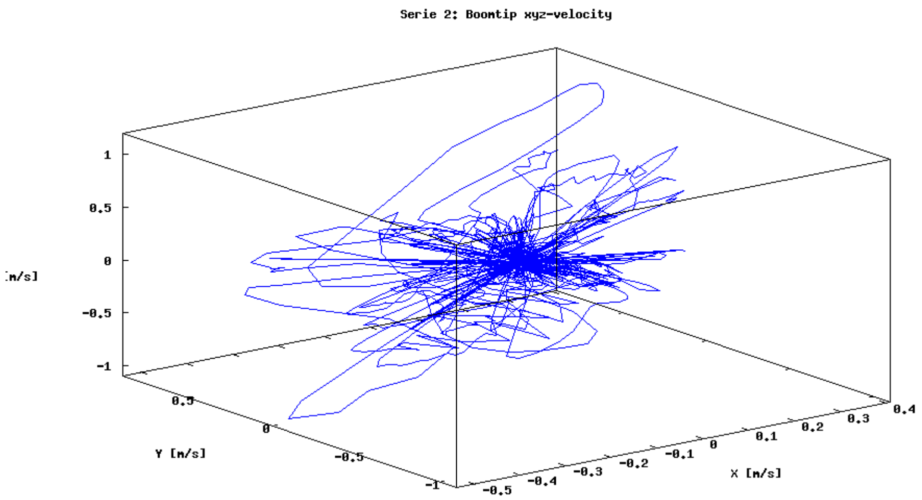


Figure 81: Operator 5 summary

B.5.1 Samples

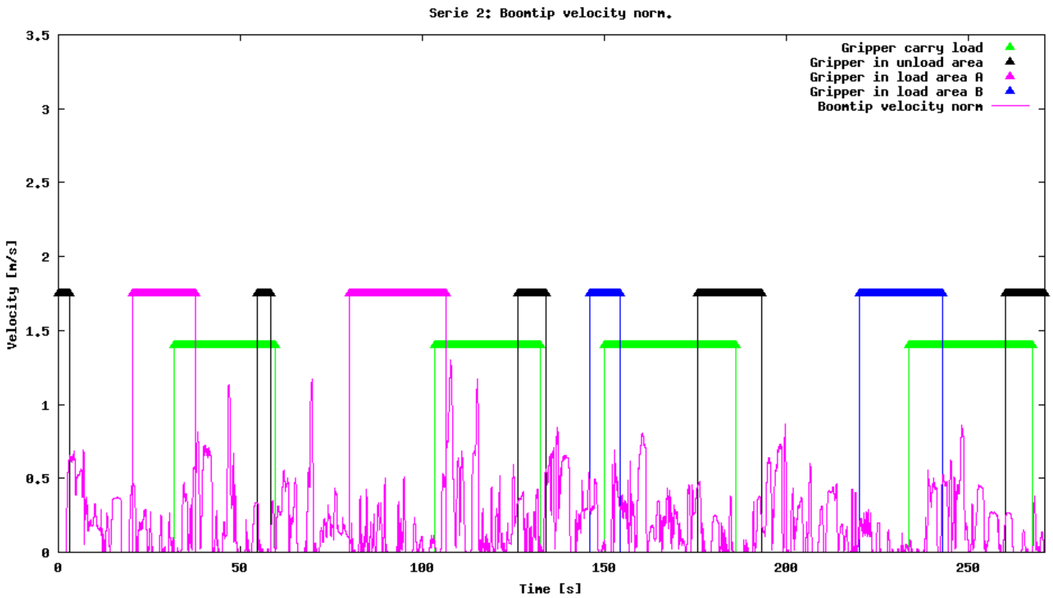


(a) Operator 5 , serie 2 – Boom–tip position, manual joint control.



(b) Operator 5 , serie 2 – Boom–tip velocity, manual joint control.

Figure 82



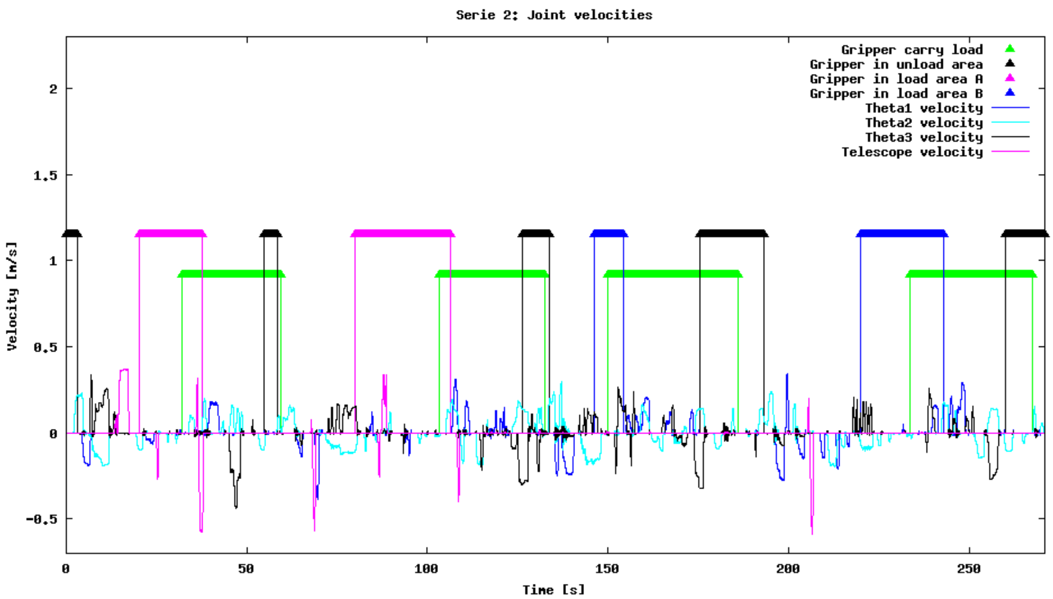
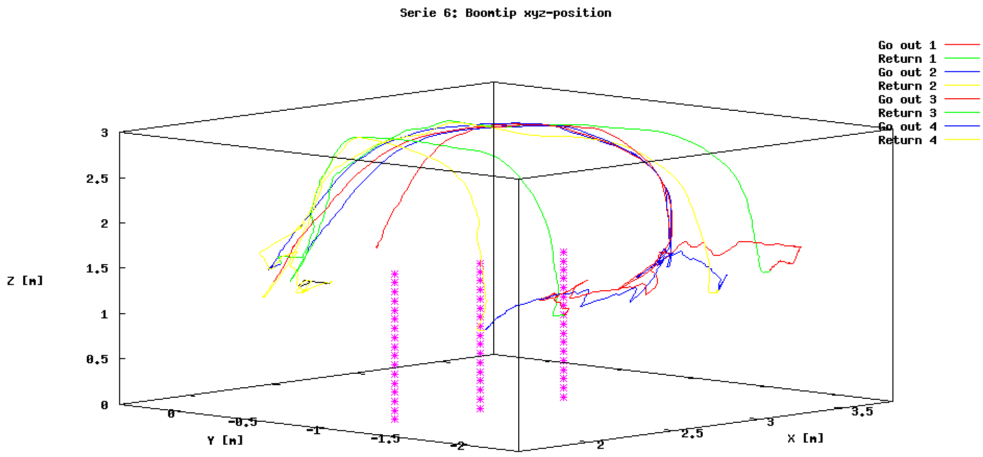
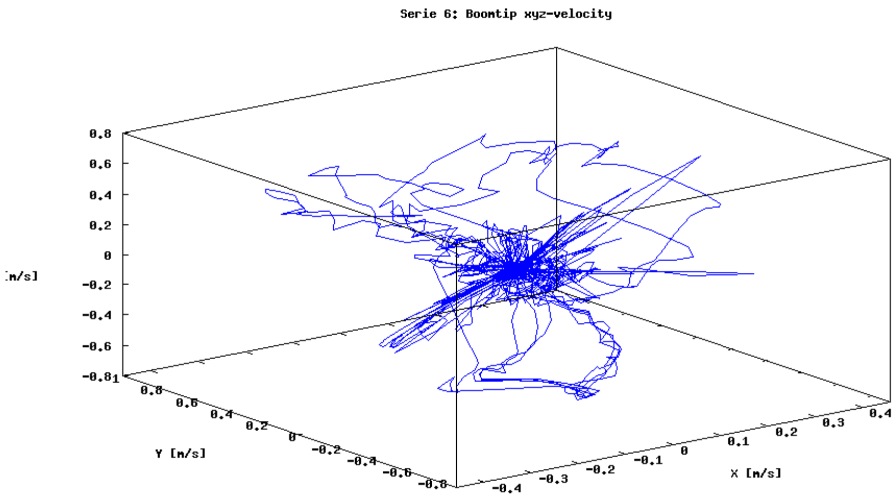


Figure 83: Operator 5 , serie 2 – Boom–tip velocity, boom–tip velocity and joint velocities versus time, manual joint control

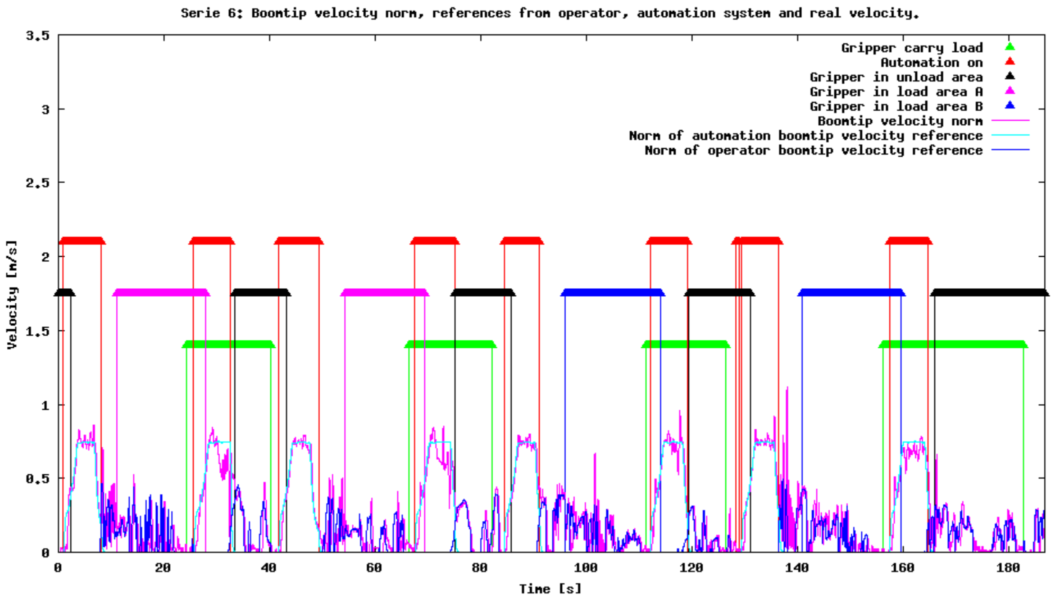


(a) Operator 5 , serie 6 – Boom–tip position, *traded control* with joint control.



(b) Operator 5 , serie 6 – Boom–tip velocity, *traded control* with joint control.

Figure 84



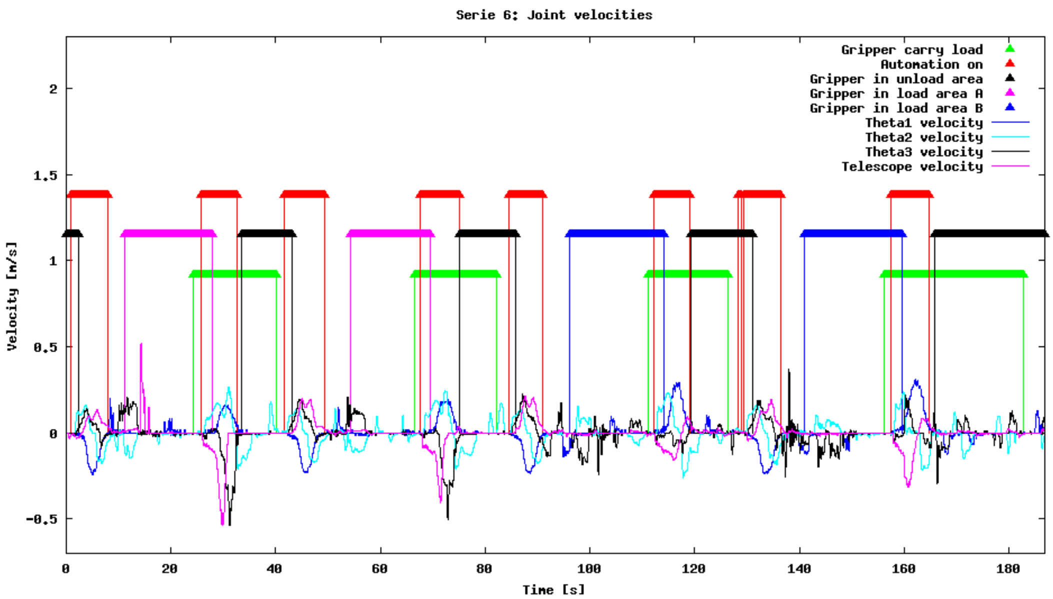
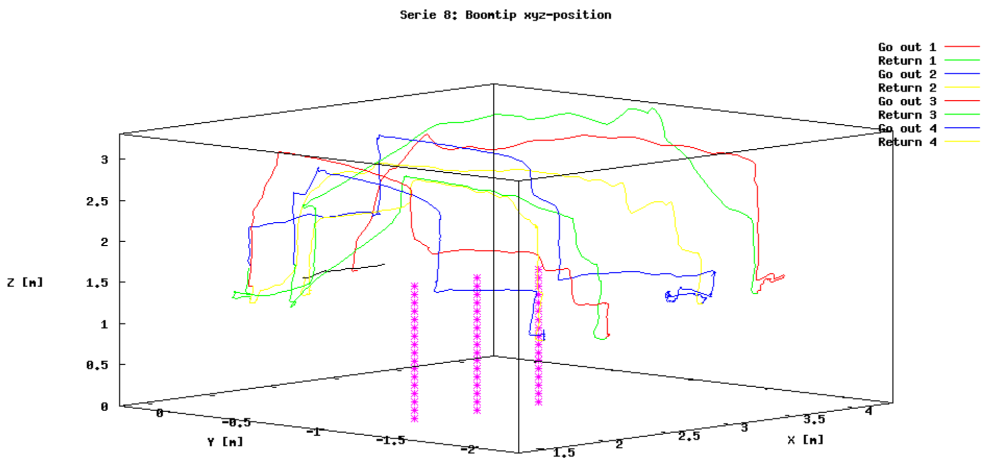
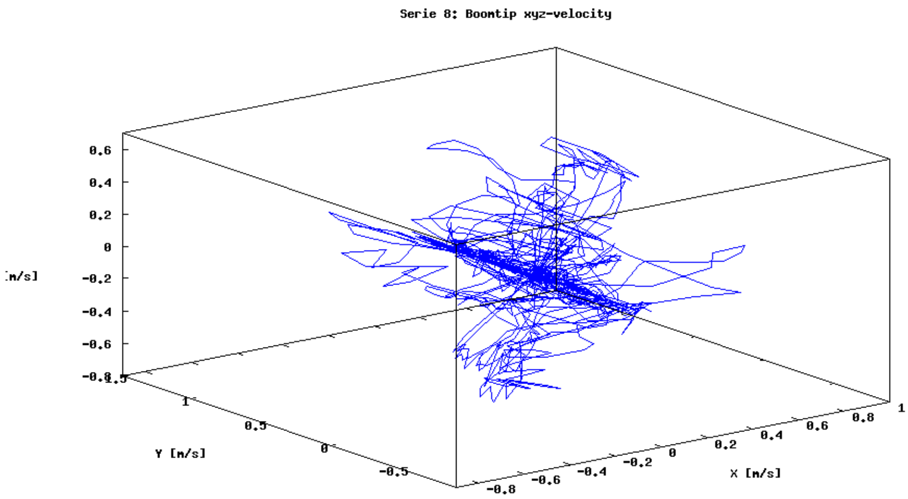


Figure 85: Operator 5 , serie 6 – Boom–tip velocity, boom–tip velocity and joint velocities versus time, *traded control* with joint control



(a) Operator 5 , serie 8 – Boom–tip position, manual boom–tip control.



(b) Operator 5 , serie 8 – Boom–tip velocity, manual boom–tip control.

Figure 86

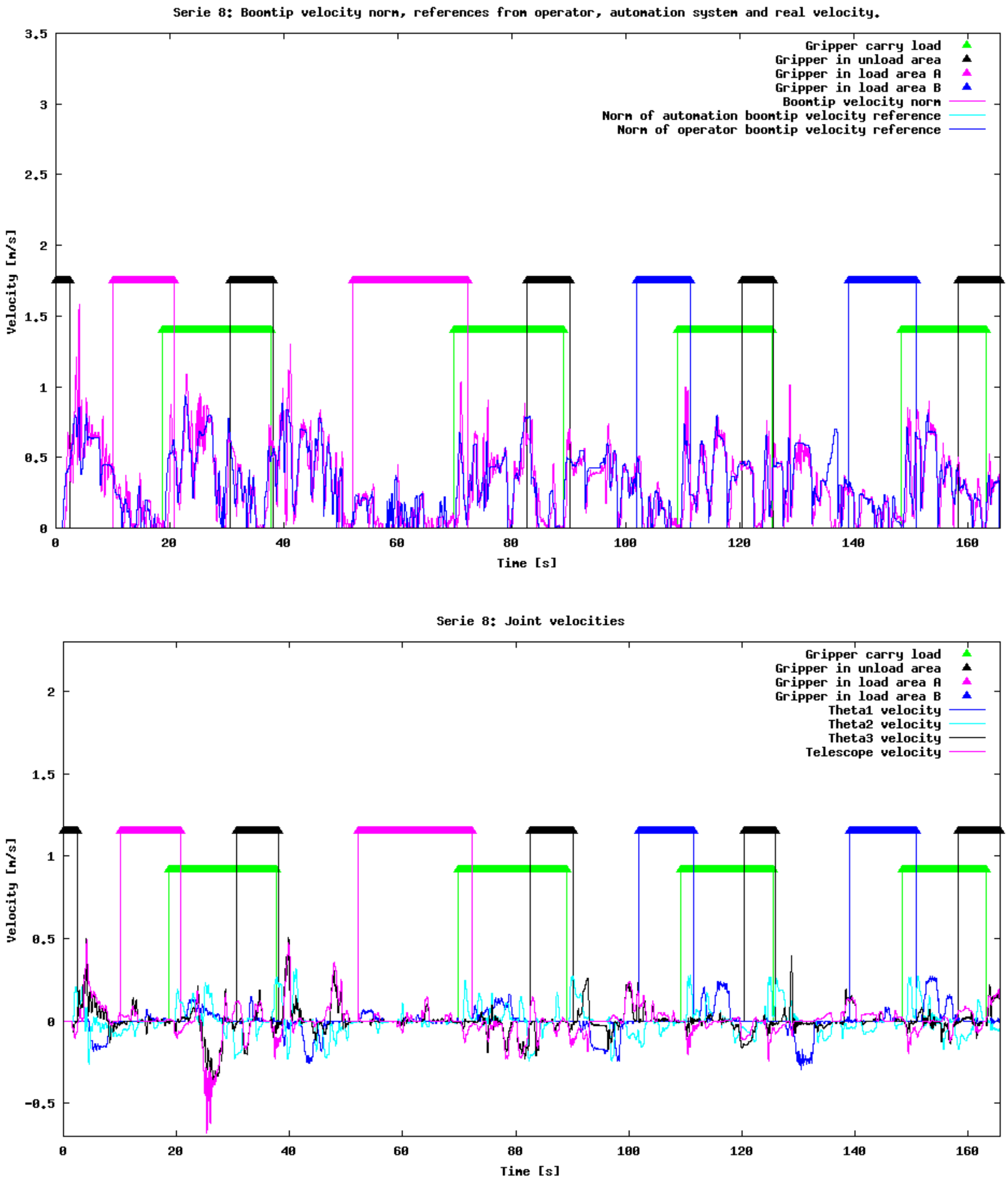
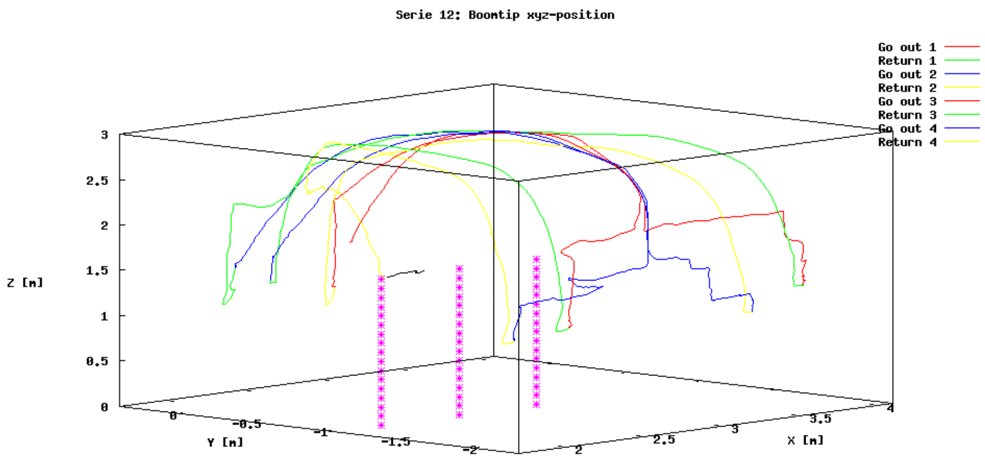
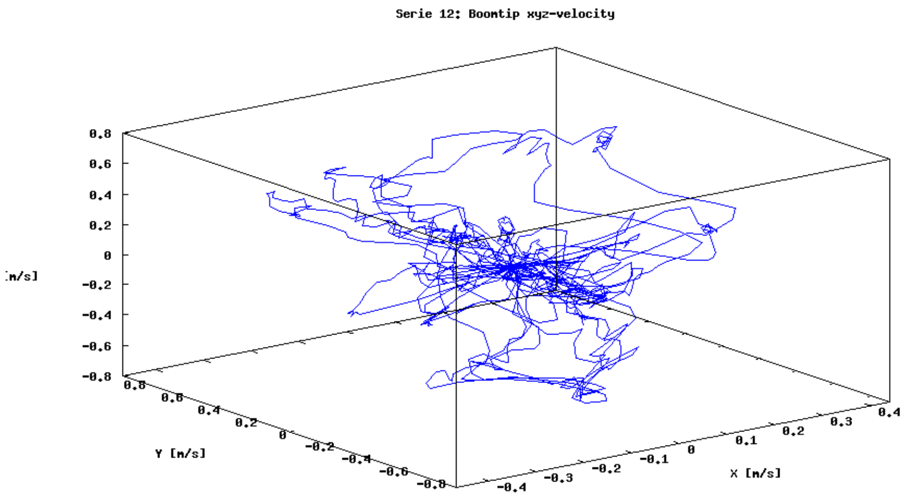


Figure 87: Operator 5 , serie 8 – Boom–tip velocity, boom–tip velocity and joint velocities versus time, manual boom–tip control



(a) Operator 5 , serie 12 – Boom–tip position, *shared control* with boom–tip control.



(b) Operator 5 , serie 12 – Boom–tip velocity, *shared control* with boom–tip control.

Figure 88

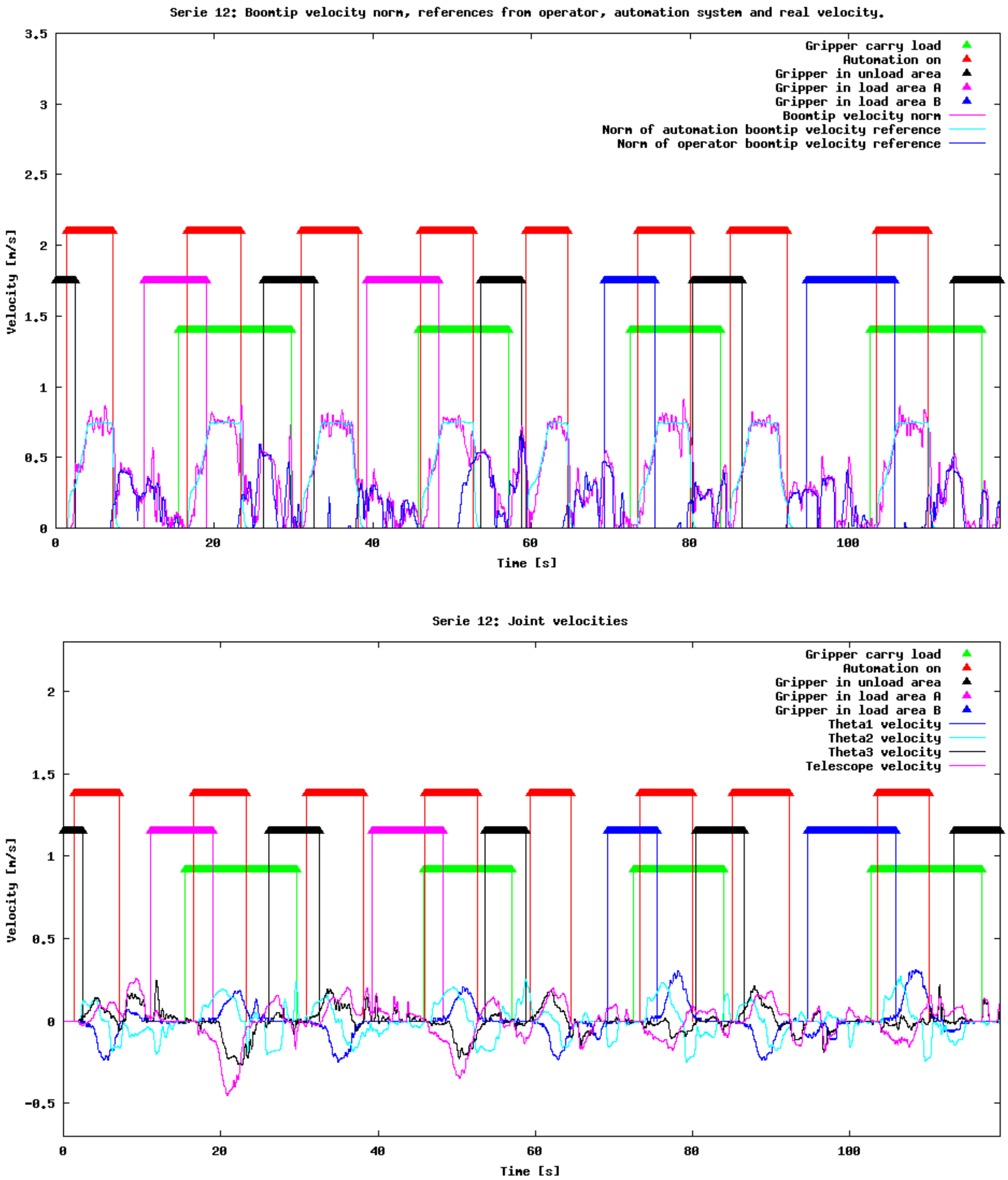
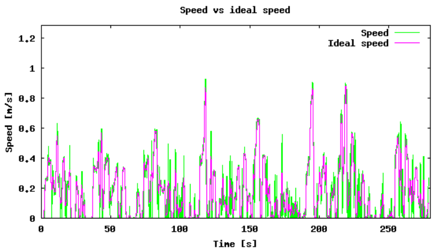
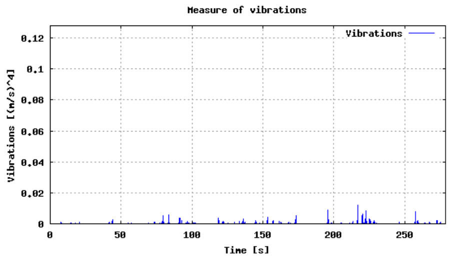


Figure 89: Operator 5 , serie 12 – Boom–tip velocity, boom–tip velocity and joint velocities versus time, *shared control* with boom–tip control

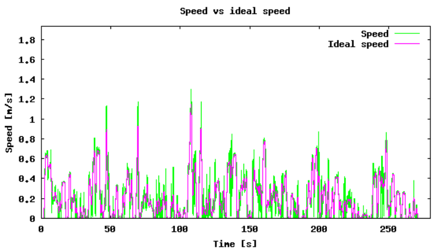
B.5.2 Boom–tip vibrations



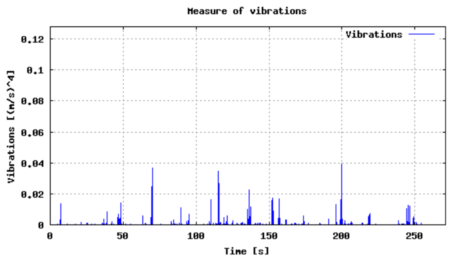
(a) Serie 1 – Ideal speed vs actual speed.



(b) Serie 1 – Vibrations.

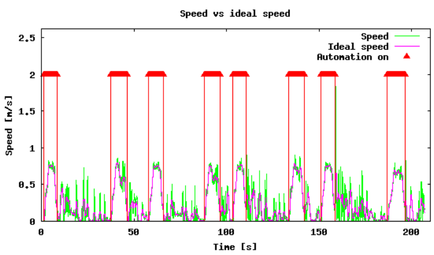


(c) Serie 2 – Ideal speed vs actual speed.

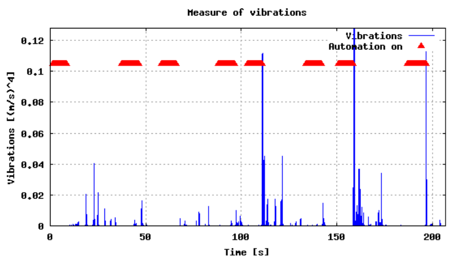


(d) Serie 2 – Vibrations.

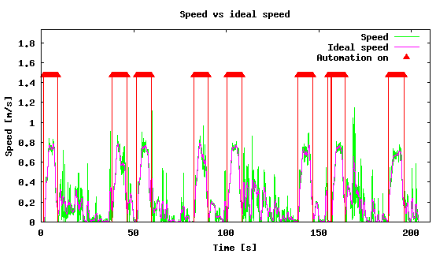
Figure 90: Operator 5 – Manual joint control



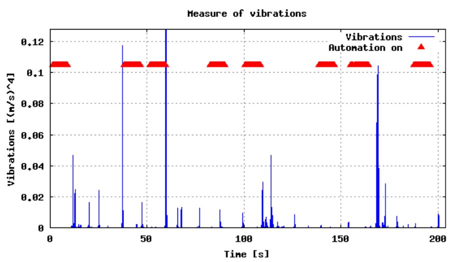
(a) Serie 3 – Ideal speed vs actual speed.



(b) Serie 3 – Vibrations.

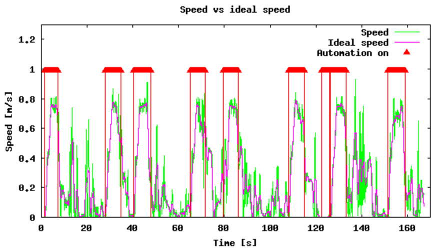


(c) Serie 4 – Ideal speed vs actual speed.

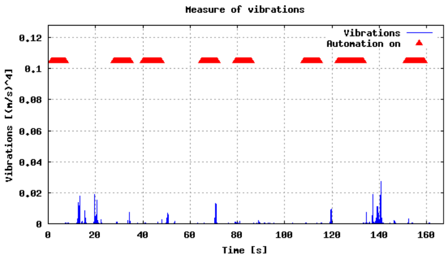


(d) Serie 4 – Vibrations.

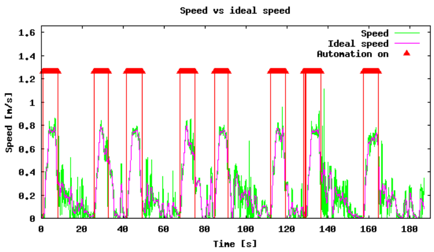
Figure 91: Operator 5 – Joint control with *traded control*.



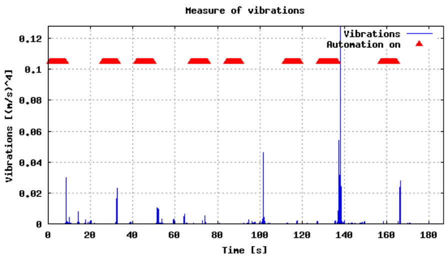
(a) Serie 5 – Ideal speed vs actual speed.



(b) Serie 5 – Vibrations.

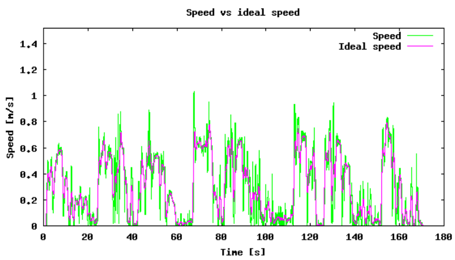


(c) Serie 6 – Ideal speed vs actual speed.

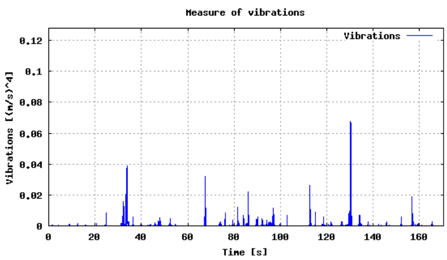


(d) Serie 6 – Vibrations.

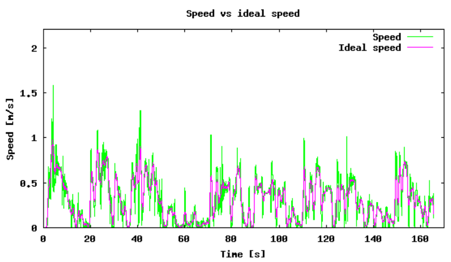
Figure 92: Operator 5 – Joint control with *shared control*.



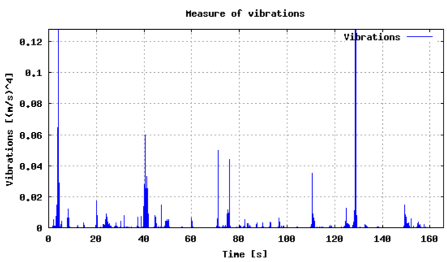
(a) Serie 7 – Ideal speed vs actual speed.



(b) Serie 7 – Vibrations.

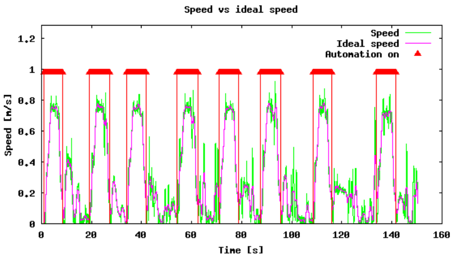


(c) Serie 8 – Ideal speed vs actual speed.

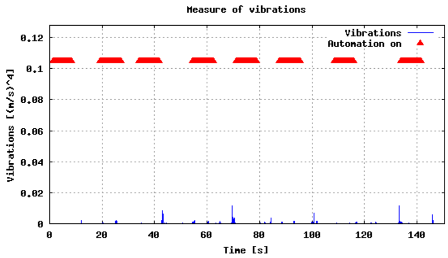


(d) Serie 8 – Vibrations.

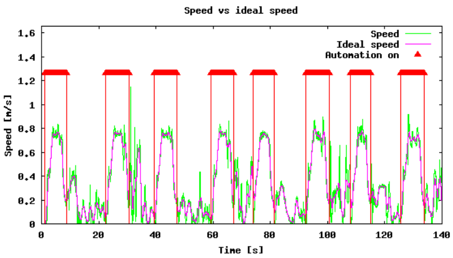
Figure 93: Operator 5 – Manual boom–tip control.



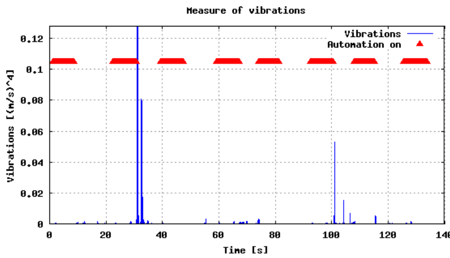
(a) Serie 9 – Ideal speed vs actual speed.



(b) Serie 9 – Vibrations.

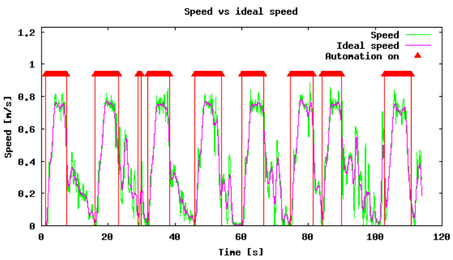


(c) Serie 10 – Ideal speed vs actual speed.

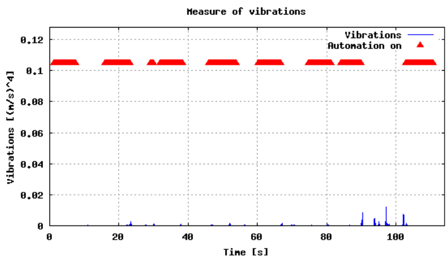


(d) Serie 10 – Vibrations.

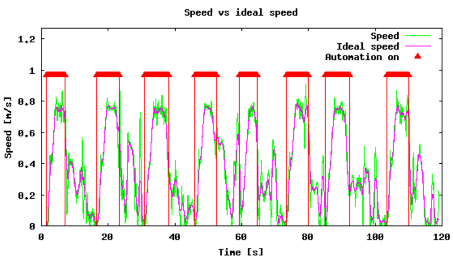
Figure 94: Operator 5 – Boom–tip control with *traded control*.



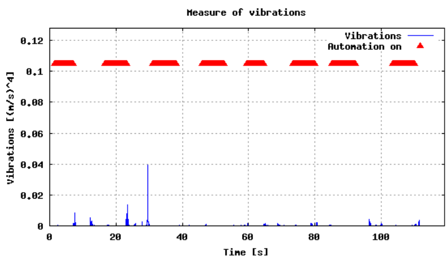
(a) Serie 11 – Ideal speed vs actual speed.



(b) Serie 11 – Vibrations.



(c) Serie 12 – Ideal speed vs actual speed.



(d) Serie 12 – Vibrations.

Figure 95: Operator 5 – Boom–tip control with *shared control*.

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