Workspace Extension in Shoulder Elevation/-Protraction Actuated, By-Wire Controlled Grasping and Squeezing in a Virtual Environment

by

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Abstract

Many users of body-powered upper extremity prostheses experience difficulties using their device and a large group abandons usage altogether. Shoulder control via Bowden cable is widely used because of the intuitive use and low cost, but requires large shoulder movements and high operating forces that, according to literature, often exceed the upper limit of around 20N that would allow for fatigue-free prolonged use. Implementing by-wire control reduces friction forces due to shorter cables, but it also allows for prosthesis control to be treated as a telemanipulation problem: workspace extension methods could prove effective in further reducing these movements and forces. To test if these methods are indeed applicable, three different modes of control - proportional gain control, non-linear variable gain control, and velocity control - were implemented in an ideal virtual environment. Performance was measured at both ends of the range of motion using an experiment based on Fitts' translational tapping task. It was hypothesised that variable gain control would improve speed during gross positioning and accuracy during fine positioning, improving overall performance, while velocity control would perform worse. The results show that the hypothesis holds, as well as improved controller performance when using a variable gain. It can be concluded that variable gain control in shoulder actuated prostheses can be beneficial and it would be worth exploring in real-life applications.

1 INTRODUCTION

Prostheses are not replacements for lost limbs [1], but rather tools for amputees to use to interact with their environment and regain their independence [2]. Current prostheses are not capable of replicating the full functionalities of their physiological counterparts and, given the immense complexity of human limbs, they may never be. Losing a hand or an arm therefore results in permanent loss of important functionalities and problems with performing even some simple, everyday tasks [1, 2].

Over two thirds of amputees are reported to have difficulties with prosthesis usage [3, 4] and around a quarter of users stop using their device altogether [3, 5]. The main reason for this phenomenon seems to lie in the (lack of) implementation of the desirable design attributes for prostheses and prosthesis control [2, 6]. Two important reasons for rejection are the uncomfortably large operating force required to operate body powered prostheses [5, 7, 8, 9] and the high mental load [7, 10] the users of battery powered prostheses experience due to the lack of inherent sensory feedback at the place of control [1, 2, 4, 6, 11, 12] in these systems. The latter is caused by requiring the user to look at the device when using it since there is no redundant information about the current state of the device available.

Normally, the brain relies on multiple sources of information regarding the positions and orientations of body parts to determine where they are, using a weighted average of all available sources. These sensory feedback signals cannot be replicated in prostheses, so some of these feedback loops now becomes open-loop rather than closed-loop and dexterity is lost [1]. In body powered prostheses, the principle of extended physiological proprioception (EPP) [10] allows the user to 'feel' the amount of force exerted on the other end of the prosthesis through the Bowden cables. The user would often still need to use visual feedback during the initial positioning of the device, since the proprioceptive information indicating the position and orientation of the limb is lost - picking up a glass or a pen, for example, require some careful manoeuvring - but after grasping, EPP should provide enough information not to drop or crush the held object. These systems also offer the most natural and subconscious control, since the body's own joints are used as control input in a way where joint position and -velocity correspond in a one-to-one relationship to the prosthesis position and -velocity, respectively [1, 2, 4]. In most externally powered systems, control is open-loop, velocity control is the common mode of control and the user relies on visual feedback only. However, These types of prostheses allow for far more versatility by offering multiple and more complex types of grasps and require little force to operate.

Since prostheses are, in essence, master-slave devices, many of the difficulties found in telemanipulation are paralleled in prosthesis design [6, 13]. In telemanipulation, most systems nowadays are designed as by-wire systems; a set of sensors and actuators are used to mimic a physical link between the master and the slave. This method of mimicking cable operated systems is believed to be very important in prosthesis development [2], as it allows for simulating inherent sensory feedback in systems that are battery powered; thus to combine the benefits of body- and battery powered systems while negating their drawbacks. The development of control interfaces with inherent sensory feedback is believed to be necessary in order to achieve significant improvement in externally powered upper limb prostheses [11]. This method has had promising results in laboratory settings using (semi-)cineplasty [11, 14]. What this method also allows for, is for the characteristics of the controller to be altered at will, adapting the device to the user and their environment via software.

One of the challenges faced by the telemanipulation field is the difference in location and scale of the master- and slave devices. Workspace mapping - either workspace extension or workspace reduction - is used to bridge the gap. Workspace extension, which will be the focus of this study, uses position- or velocity control (or a combination of both) to translate the position of the master device to, respectively, the position or velocity of the slave device [15, 16]. The controller can be designed in a way that changes the behaviour of the device depending on the situation. The main goal of this thesis is to find which type of workspace extension method would be most beneficial across the range of motion in a shoulder shrug controlled, by-wire grasping prosthesis. 'Shrug,' in this paper, refers to the combination of shoulder elevation and -protraction.

The proposed research question: "Can workspace extension methods be used to improve the overall task- and controller performance for a shoulder shrug controlled, virtual, by-wire grasping prosthesis in a one-dimensional grasp-and-squeeze task based off of Fitts' Tapping Task, without sacrificing performance in part of the range of motion?"

2 EXPERIMENT DESIGN

2.1 Design background

In this section, the design methodology for both prostheses and teleoperation devices is explained.

Prosthesis design follows a set of design principles to make sure the device is both useful and usable. A prosthesis has to be, for example, lightweight and aesthetically pleasing. The focus of this study revolves around the design principles of the device being intuitive and physically and mentally little demanding to use [7]. These devices have to be comfortable to use for the better part of the day; muscle fatigue can become a problem during prolonged use if the device is too heavy or the operating forces are too high [5, 7, 8, 9, 13]. Body-powered prostheses are actuated via Bowden cables, in which friction forces and the spring antagonising the voluntary movement make that for a pinch force of 15N, an operating force of between 33N and 131N have been measured for different models of grasping devices. For prolonged use, operating forces should be below 20% of the user's maximum operating force, which was found to be 270 +- 106N for a 'shrug' motion [17], allowing a lower bound of 32.8N for prolonged use. This study was conducted with 50 'normal' subjects (without defects), whose characteristics, as well as the measurement procedure, were not described. More recent studies reported that, for prolonged use by users with defects, control forces should be below 23N to ensure fatigue free use in 90% of users, or be targeted at the average fatigue free force levels of 38N for females and 66N for males [18]; 10-20N for prolonged use was found for users with defects in another study, with forces over 40N found to distort proprioceptive feedback [7]. Furthermore, the range of motion for shoulder shrug is between 4 cm [19] and 5.6 cm [17]. Having to operate at the maximum of this range to grasp small objects is tedious and uncomfortable, and muscle force declines towards the end of the range of motion.

In telemanipulation, there often is a discrepancy between the scale of the master- and slave side of the device. To adjust for this, workspace extension methods can be applied to alter the relationship between the movements of the master and those of the slave to better suit the application. Workspace extension methods use position- and/or velocity control to dictate the relationship between the movements of the master and the slave, but most are not suitable for use in prostheses because they lack the intuitive position-position relationship that makes cable-operated systems so easy to use [1, 2, 4]. To ensure the system is intuitive and that the mental load for the user is low, nulling compliance is an important trait; the given that when the master has returned to its starting position, so has the slave [15, 20]. This leaves scaling, either constant or variable, as this is the only method that preserves nulling compliance. Human operators adapt well to a linear variable gain [15], but this is not useful for grasping; This type of gain favours speed at one end of the range of motion and precision at the other, but precision can be required both at the start or at the end of the range of motion depending on the situation. A nonlinear gain would be more applicable, but operators do no adapt as well to to these gains [15]. Another possible option is velocity control, which is widely used in EMG-controlled prostheses; the position of the master dictates the velocity of the slave. This method, however, performs worse than EPP control in elbow flexion and wrist rotation tasks when shoulder movements are used as a control movement, but no data on grasping using shoulder control was found in literature.

2.2 Design of By-Wire Prosthetic

To perform an experiment on healthy subjects, a simulated prosthesis had to be built. A mechanical prosthesis simulator was available; a device that puts a shoulder harness-controlled prehensor in front of the subject's hand. When connecting the shoulder harness and prehensor to a master-slave device instead of directly to each other, a by-wire controlled system would be achieved. With the experiment in mind, there was decided to opt for a virtual slave instead; this approach removes all sensor- and motor noise from the slave side of the device, removes all external influences on the slave (such as gravity and friction) and ensures a perfectly constant experimental environment. This approach allows for a very close comparison of the subjects' performance when using controller modes, since no other factors are changed throughout the experiment.

The master-slave system will be controlled by a Bachmann real-time controller. This device uses a Simulink model to provide the right output to the feedback motor considering the input it receives from the LVDT. The reference slave positions are then read by a laptop running MatLab, and projected onto a monitor. Since there is no discrepancy between the actual position of the slave and the reference position of the slave, the virtual slave is 'perfect' and, though not possible in the physical world, very useful for experimental purposes.

The wiring description for the Bachmann real-time controller is shown in Appendix 7.

2.3 Design methodology

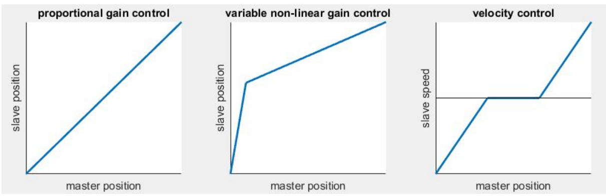

Figure 1: *Controller modes: master position (horizontal axis) vs slave position (vertical axis) for proportional gain (baseline), non-linear variable gain with transition at the moment of contact with an object, and velocity control with a dead zone*

Based on the literature, there was decided on three controller modes: proportional gain position control as a baseline to mimic a 'normal' cable-operated prosthesis, non-linear variable gain position control with a transition at the moment of contact with an object, and velocity control (see figure 1). To test performance across the range of motion, two object sizes were chosen: a large object at 8cm and a small object at 2cm. The units were arbitrary and just for purpose of definition; the visuals were projected on a 21 inch monitor as to prevent small targets to be visually unclear, and were a constant factor across the experiment as every subject used the same monitor. The experimental conditions are defined in table 1.

	proportional gain	variable gain	velocity control
small object	11	12	13
large object	21	22	23

Table 1: *Experimental conditions*

The hypothesis states that for large objects, no differences will be found between proportional- and velocity gain; velocity control will come in last. For small objects, the variable gain will have a clear advantage over and will be more comfortable than the proportional gain; again, both will be superior compared to velocity gain.

Task characteristics	Forces within acceptable range. Grasping and squeezing large and small objects. Movements across the entire range of motion. Time hold on target sufficiently long to prevent sweeping.
Device characteristics	Acceptable gains. Input required no larger than 5cm. Non-linear variable gain.

Table 2: *Required task- and device characteristics*

Since the task was a simplified, abstract representation of a prosthesis and the virtual slave was defined as a perfect slave (no discrepancy or delay between set point and position), the design largely came down to choice. Independent variables should differ enough to be clearly different and gains should be high enough to be satisfying to use but low enough to be controllable. The design characteristics are defined in table 2.

The slave was defined to be 10cm long for simplicity. Targets were uniformly distributed across the objects, with constant difficulty rating defined for a target of 0.5cm wide at a distance of 6 cm from the starting position. This was an arbitrary design choice. Objects were defined to be 2 and 8 cm long, forces were 18N including pretension at maximum compression due to hardware limitations, and time to hold on target was set to 2.5 seconds iteratively during the pilot study.

Variable gain was set to 1.5 to make a clear difference but not remove the gap before the large object completely. The velocity control gain was set to 0.0007 iteratively during pilot; this gain, multiplied by the distance from the 1cm dead zone centred at 1cm from the starting position, equals the distance the slave moves per sample at 2kHz. The master's range of motion is 4.29cm due to hardware limitations.

3 METHOD

3.1 Participants

Twenty healthy, male subjects between the ages of 18 and 59 ($\alpha = 26.1$, $\sigma = 8.4$) voluntarily performed the experiment. The majority of the subjects was right-handed (85%) and none had impaired vision or movement. None of the subjects had any experience using a shoulder harness. All participants gave their informed consent (Appendix 3). The experiment was approved by the Delft university of Technology Human Research Ethics Committee (Appendices 5 and 6).

3.2 Experimental setup

The experimental setup is shown in figures 2 and 3. The participant was shown the stylised virtual prosthesis with the object and target represented in red and green, respectively. The shoulder harness was connected to the input device via a Bowden cable and fitted onto the subject's shoulder blades using double sided- and sports tape in a way that the entire range of motion of the master device could be reached comfortably. The emergency button, which cuts the power to the actuator, is placed to be easily accessible to both the subject and the supervisor. The setup was tested on usability, reproducibility and robustness during the pilot study.

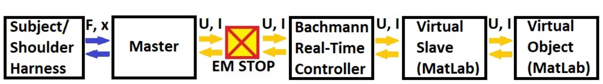

Figure 2: *Schematic drawing of the setup. Mechanical interactions are depicted by blue arrows; electrical signals (and thus also virtual 'physical' interactions) by yellow arrows. The shoulder harness is anchored to the subject and they move as one. The different controllers as shown in figure 1 are implemented by the Bachmann real-time controller.*

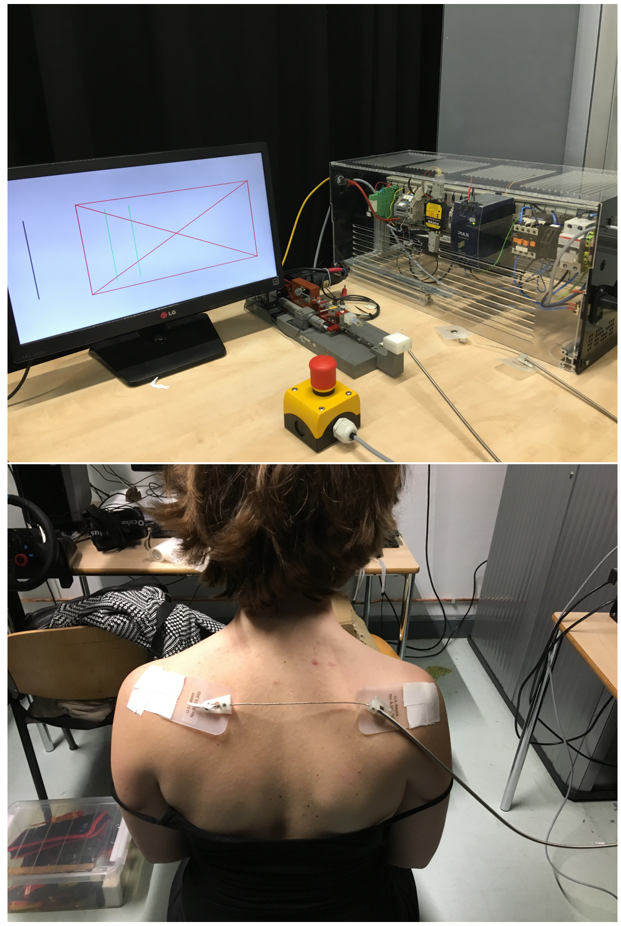

Figure 3: *Full setup showing the master device with shoulder harness, emergency stop button, Bachmann real-time controller and projection of the virtual slave (a) and the shoulder harness anchored to a subject (b). Subject gave permission to use this picture.*

3.3 Apparatus

The experiment was performed using the 'Prosthetic Hand Simulator', which consists of one side of a one-dimensional, bilateral master-slave system, shown in figure 4a. The position of the red arm is measured by an LVDT (silver rod) with a maximum displacement of 4.29cm and the feedback forces are provided by an electric motor (black) capable of providing a static torque to exert a maximum of 18N onto the bowden cable. The simulink model runs on a Bachmann real time computer, shown in figure 4b, at a frequency of 2kHz. The virtual slave (see figure 5) is sampled and projected onto the monitor at a rate of 60Hz. Feedback forces are applied to the master device at 2kHz. See Appendices 4 and 7 for the device report and wiring description, respectively.

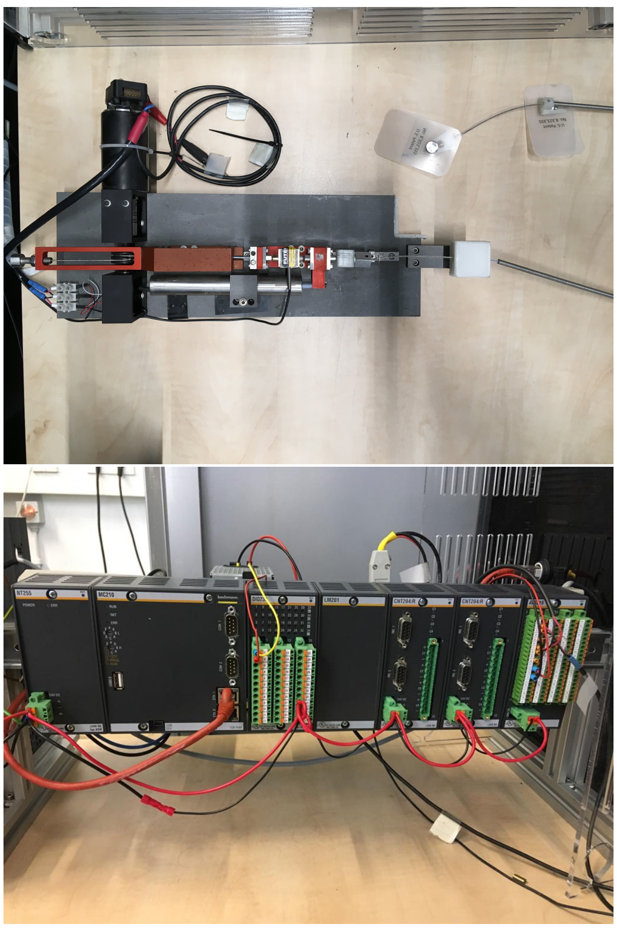

Figure 4: *Master device consisting of an electric motor (black cylinder), LVDT (silver rod) and a translating rod (red) (a) and Bachmann real-time controller (b).*

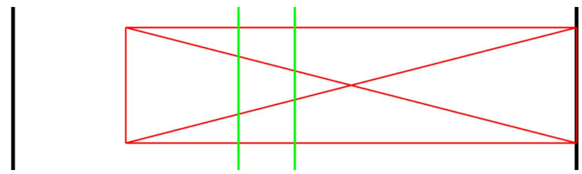

Figure 5: *Drawing of the virtual slave and environment. The black lines depict the slave (left is moving, right is stationary), the spring object is depicted by the red block and the green lines depict the borders of the target area.*

3.4 Task description

The participants were asked to perform a one degree of freedom translational pointing task, which was based on Fitts' translational tapping task [21] The task was to move the moving part of the prosthesis from the starting position to within the target area as quickly as possible and hold it there for two seconds. The task started when, after a three second countdown, the prosthesis, object and target were made visible. After the trial was completed, the visuals were set to invisible and a message was shown prompting the subject to return to the starting position. This process was repeated until all trials were completed.

3.5 Experimental design

A within subject telemanipulation experiment was performed. The six experimental conditions (three controllers, two object sizes) were randomised by first blocking the orders in which the controllers were offered to prevent the learning effect on the device to bias the data and then blocking the order in which the objects were offered to spread the more fatiguing trials uniformly. The experiment started with an informed consent (Appendix 3) and a task- and safety briefing (Appendix 2). Then, the demo environment was initiated, which loads the proportional gain controller, a random object and random target, but does not register target hits. This mode is used to show the subject how the interaction between the user, device and slave works and to fit the shoulder harness properly and comfortably to the subject. After that, the experiment started and the subject was told he had five practise trials to get used to the controller that was then initiated. These trials would still be recorded, but were meant to reduce stress and to promote focus at the ‘real’ trials. After the practise trials, 20 more trials were performed. Finally, the subject was asked to rate his experience and elaborate on his rating.

3.6 Data acquisition

The positions of the master and the virtual slave were recorded at a sample frequency of 2kHz. Before analysing the data, the raw data was filtered using a moving average filter with a window size of 10.. This reduced the noise in the signal to an order of magnitude of 10e-5.

3.7 Metrics

To determine task performance, time [s] and Fitts’ Index of Performance [bits/s] were used as metrics. The time metric was then divided into total positioning time, gross positioning time, fine positioning time and time to contact. This is visualised in figure 6.

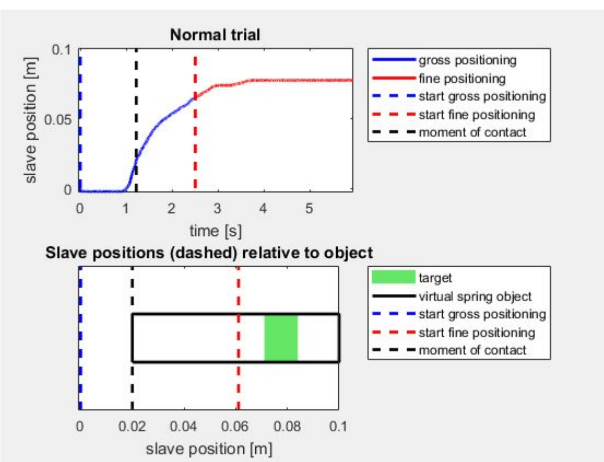

Figure 6: *A normal trial using the proportional gain controller mode (top) and the corresponding slave positions (bottom)*

Total positioning time

total positioning time was defined as the time from the start of the trial until the completion of the trial.

Gross positioning time

gross positioning time was defined as the time from the start of the trial until the slave is within 1cm of the target area.

Fine positioning time

fine positioning time was defined as the time required to complete the trial after gross positioning time.

Time to contact

time to contact was defined as the time between the start of the trial and first contact between the slave and the object.

Fitts’ Index of Performance

Fitts’ Index of Performance was calculated by dividing Fitts’ Index of Difficulty (ID) by the total positioning time,

$$ID = log_2\left(\frac{2D}{W}\right)$$
$$IP = \frac{ID}{t}$$

where D is the distance from the starting position of the slave to the centre of the target area and W is the width of the target area.

Mean absolute jerk normalised by peak speed

To determine controller performance, mean absolute jerk normalised by peak speed of the slave was used as a metric. Jerk is a measure of smoothness of a movement; By normalising by peak speed, the effect of changes in overall speed on the metric are mitigated and the metric is a measure of smoothness only. Smoothness is a measure of how controlled a movement can be performed by the operator [22].

3.8 Statistical analysis

Before the statistical analysis was performed, some assumptions had to be justified. At 1500 data points over 20 subjects, the effects of individual differences between the subjects on the data can likely be neglected. To test this assumption, the average time for large object trials was divided by the average time for small object trials for every controller mode for every subject. The spread of this ratio shows subject consistency. Then, a cut-off for practise trials was decided. Participants were told the first five trials were practise trials, but in reality all trials were recorded. Mean and standard deviation of total task completion time were calculated for all six experimental conditions, and cut-off was decided at the trial number where the performance seemed to stagnate and the learning effect was mitigated. After that, a one-way repeated measures ANOVA was performed on the entire data set to find differences between the six conditions. Mauchly's sphericity test was performed to test for equality of variance of the differences between the conditions, and a Greenhouse-Geisser correction was applied whenever the test failed. Since performance on both sides of the range of motion had to be considered, it was necessary to treat the object size groups ('small' and 'large') as independent data sets. To check if this would be allowed, a one-way repeated ANOVA was performed on the full data set once again, this time comparing only the object size groups. Finally, one-way repeated measures ANOVAs were performed on the two groups to compare the three control modes and post hoc analysis showed the effects within individual metrics.

Since the metrics do not necessarily have to be independent, a Bonferoni correction could be applied. This method attempts to correct for false positives in post hoc testing caused by dependence between metrics by dividing the value for alpha that is chosen as threshold for significance by the amount of hypotheses that are considered, in this case six metrics. Due to the conservative nature of this correction, both the 'normal' and Bonferoni significance will be shown in the results section.

4 RESULTS

In this section, the acquired data is analysed. The raw data for each subject is shown in Appendix 1.

4.1 Individual performance ratio

In this section, the subjects' average ratio between task completion time for large and small objects for every controller and the standard deviations are shown to determine whether or not the assumption that individual differences do not bias the data holds. If so, the entire data set will be treated as independent observations. The results are shown in table 3.

	μ	σ
proportional gain	1.1888	0.1005
variable gain	1.1858	0.1232
velocity control	1.3206	0.5226

Table 3: *Ratio between average task completion time for large objects to small objects*

Considering the proportional- and variable gain controllers, the small standard deviation shows that performance is consistent across these controllers. A subject that performs better while using one controller will not only perform better in another, but equally as much better. Because of the consistency, it can be assumed that the human can be neglected as a factor and the data points can be treated independently. This does not hold for the velocity control mode.

4.2 Practise trial cut-off

In this section, the optimal cut-off of 'practise' trials to mitigate the learning effect is estimated. For every experimental condition, the mean and standard deviation of the total task completion time have been calculated for when all trials were used and for when the first 1 to 23 trials had been discarded.

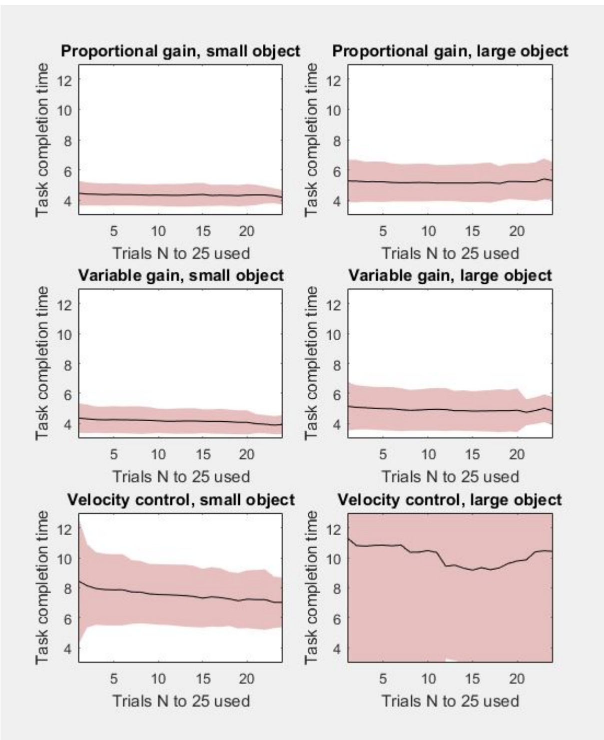

Figure 7: *Task completion time means and standard deviations when only trials N to 25 are used.*

The results are shown in figure 7. The solid line shows the average task completion time and the red band shows the standard deviation. Based on this experiment, there was decided to discard the first seven trials. Also, there was decided to discard velocity control altogether as a viable option since the averages and spread are far inferior to the other control modes. This was in accordance with literature on different prosthetic movements, where velocity control was inferior to position control for shoulder movement inputs [23, 24]. Velocity control data will therefore not be further analysed. figure 8 shows the data for proportional- and variable gain control on a smaller scale, to show the learning curve more clearly.

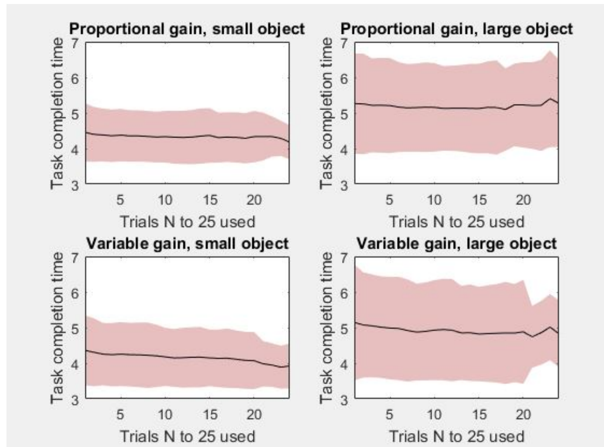

Figure 8: *Task completion time means and standard deviations when only trials N to 25 are used. Velocity control removed for readability*

4.3 Analysis of variance

In this section, the means and standard deviations are shown for all metrics for every experimental condition and the results of the ANOVAs are shown. A p-value lower than 0.05 is considered significant ($\alpha = 0.05$). After applying the Bonferoni correction, this is reflected by a p-value lower than 0.0083.

The initial one-way repeated measures ANOVA violated sphericity. After applying a Greenhouse-Geisser correction, a strong significant effect was found (F = 838.37, p = 0). When comparing the size groups during another one-way repeated measures ANOVA, a Greenhouse-Geisser correction was again required and the effect was again strong (F = 42.65, p = 1.0066e-10). It was now assumed justified to treat the size groups as independent data sets.

Both size groups, again, violated sphericity. After applying a Greenhouse-Geisser correction, a significant difference between the controllers was found in both groups (small: F = 701.06, p¡0.0001; large: F = 255.91, p¡0.0001). The post hoc analysis provides insight in the nature of these differences. Figure 9 shows an overview of the results that will be discussed in this section.

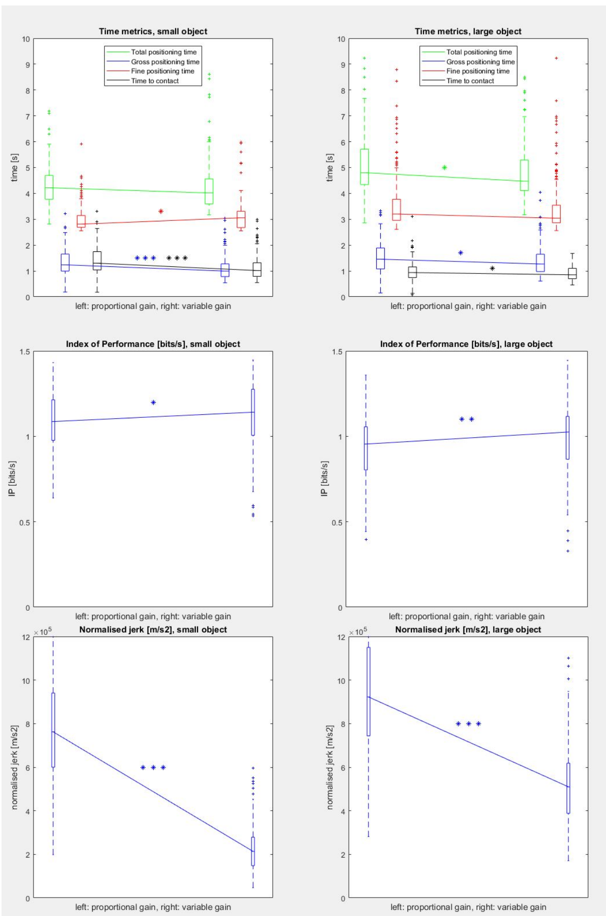

Figure 9: *Comparison of all metrics. All metrics are based on slave data. Significance is shown as stars, with* $*$*:* $p < 0.05$, $**$*:* $p < 0.0083$ *(Bonferoni significant for* α *= 0.05) and* $***$*:* $p < 0.0001$

Total positioning time

Post hoc analysis showed a significant improvement in total positioning time for grasping larger objects when using the variable gain controller when no correction was applied (p=0.0437), but analysis after applying a Bonferoni correction does not result in significant differences. No significant differences were detected for grasping smaller objects (p=0.1843). See table 4.

total positioning time	prop. gain $\mu(\sigma)$	variable gain $\mu(\sigma)$	F	$p > F$
small object	4.3404 (0.7164)	4.2242 (0.9197)	1.77	0.1843
large object	5.1504 (1.2403)	4.8746 (1.3590)	4.1	0.0437

Table 4: *Means, standard deviations, F- and p-values for total positioning time.*

Gross positioning time

A significant improvement was found for gross positioning time for grasping of all sizes, when using the variable gain controller. When grasping smaller objects, the effect was stronger (p¡0.0001) than for grasping larger objects (p=0.0111). The significant effect persists for grasping small objects after a Bonferoni correction, but not for grasping large objects. See table 5.

gross positioning time	prop. gain $\mu(\sigma)$	variable gain $\mu(\sigma)$	F	$p > F$
small object	1.3441 (0.4780)	1.1069 (0.4494)	23.18	<0.0001
large object	1.5139 (0.6007)	1.3609 (0.5437)	6.52	0.0111

Table 5: *Means, standard deviations, F- and p-values for gross positioning time.*

Fine positioning time

A significant effect was found in fine positioning time when grasping smaller objects. Using the variable gain controller increases the time required for fine movements (p=0.0333). When grasping larger objects, no effects were found (p=0.3513). After applying a Bonferoni correction, no significant effects were found for either size group. See table 6.

fine positioning time	prop. gain $\mu(\sigma)$	variable gain $\mu(\sigma)$	F	$p > F$
small object	2.9963 (0.4829)	3.1173 (0.5807)	4.57	0.0333
large object	3.6365 (1.1673)	3.5137 (1.3386)	0.87	0.3513

Table 6: *Means, standard deviations, F- and p-values for fine positioning time.*

Time to contact

A significant improvement in the time required from the starting position until grasping the object was found when using the variable gain controller for both small and large objects. The effect was stronger for grasping smaller objects (p¡0.0001) than for larger objects (p=0.0223). The significant effect persists for grasping small objects after applying a Bonferoni correction, but not for grasping large objects. See table 7.

time to contact	prop. gain $\mu(\sigma)$	variable gain $\mu(\sigma)$	F	$p > F$
small object	1.4187 (0.5190)	1.1295 (0.4601)	30.8	<0.0001
large object	0.9918 (0.3606)	0.9155 (0.2684)	5.27	0.0223

Table 7: *Means, standard deviations, F- and p-values for time to contact.*

Fitts' Index of Performance

Significant improvements in performance were found for both small and large object tasks. The effect was stronger for larger objects (p=0.0045) than for small objects (p=0.0243). The significant effect persists for grasping large objects after applying a Bonferoni correction, but when grasping small objects the effect is no longer significant. See table 8.

Fitts' IP	prop. gain $\mu(\sigma)$	variable gain $\mu(\sigma)$	F	$p > F$
small object	1.0824 (0.1631)	1.1252 (0.1928)	5.11	0.0243
large object	0.9325 (0.1879)	0.9897 (0.1934)	8.19	0.0045

Table 8: *Means, standard deviations, F- and p-values for Fitts' Index of Performance.*

Mean absolute jerk normalised by peak speed

A significant improvement in smoothness was found when using the variable gain controller when grasping both small and large objects. This effect was very strong for both size groups (p¡0.0001). This effect persists after a Bonferoni correction is applied. See table 9.

norm. jerk	prop. gain $\mu(\sigma)$	variable gain $\mu(\sigma)$	F	$p > F$
small object	7.6490 (2.4951)	2.2385 (1.0546)	701.06	<0.0001
large object	9.5089 (3.1278)	5.2269 (1.8381)	255.91	<0.0001

Table 9: *Means, standard deviations, F- and p-values for mean absolute jerk normalised by peak speed.*

5 DISCUSSION

The primary goal of this study was to find out if workspace extension methods can be used to improve task- and controller performance in either the entire or partial range of motion for shoulder shrug operated, by wire controlled grasping prostheses without sacrificing performance in another part of the range of motion. By 'shrug', in the scope of this paper, is meant a combination of shoulder elevation and -protraction. The proportional gain controller was used as a baseline and represents a 'normal' behaviour for a cable operated prosthesis, with the added benefits of reduced friction and spring forces thanks to the by-wire control method. The hypothesis was that the variable gain would improve performance because of the shifted speed-accuracy trade-off in the small objects tasks, while performing similarly to the baseline controller for large object tasks; the velocity control gain would perform worse in task performance compared to baseline performance. During data analysis, it became apparent that the velocity gain controller's task performance was so inferior to the other controllers to the extent that further analysis was deemed unnecessary, and the controller was removed from the data set. The statistical analysis further seemed to indicate that the hypothesis was mostly correct, as task- and controller performance were increased by the variable gain; with the exception being that the benefits appeared to mostly impact the large objects rather than the small objects.

The Bonferoni correction is often criticised for being too conservative, since the way it reduces false positives has a tendency to introduce false negatives. Since the uncorrected analysis, due to possible dependency between metrics, might have been influenced by false positives and the corrected analysis by false negatives, the truth was assumed to lie somewhere in the middle and the decision was made to show both the corrected and uncorrected significance levels.

5.1 Interpretation of effects on metrics

Gross positioning time

Gross positioning time significantly improved over the entire range of motion when using the variable gain controller, compared to the proportional gain controller. This effect was strongest for grasping smaller objects, which was to be expected since for those tasks, the gross positioning took place mainly before contact with the object was established; the gain, and thus speed, was higher for most of the gross positioning compared to the proportional gain. For large objects, the slave will still receive a 'head start' because of the increased speed before contact is established, the non-linearity will be less noticeable - especially when the target is farther from the contact point - and the fast motion is performed with slightly increased accuracy. Overall, these result in an improved gross positioning time.

Fine positioning time

For grasping small objects with the variable gain, the non-linearity was a lot more noticeable than for larger objects. This resulted in a sudden decrease in movement speed after contact with the object was established. The fine positioning time was significantly longer when using the variable gain because of this. This was expected, as the variable gain controller was designed to favour accuracy over speed when grasping small objects.The average fine positioning time, however, only increased by about a tenth of a second. The controller was designed to be similar to the proportional gain when grasping large objects, and the absence of an effect between the proportional- and variable gain for large objects indicates this was done successfully.

Time to contact

The time to contact significantly improved when using the variable gain controller over the entire range of motion. This was to be expected; This controller increases the gain when no contact is established yet, increasing the speed at which the slave moves.

Total positioning time

There were no significant differences in total positioning time when grasping small objects, but there were for grasping large objects. What this seems to indicate is that the slight increase in movement speed in the first part of the movement, combined with the slightly increased precision during the fast part of the movement, allows for an increase in overall speed when grasping larger objects. The non-linearity when grasping smaller objects is more noticeable than when grasping large objects and requires more time to deal with, nullifying the speed benefits for smaller objects but improving accuracy when the object is grasped.

Fitts' Index of Performance

Performance significantly increased over the entire range of motion when using the variable gain controller compared to the proportional gain controller. The time required to perform the movement either stayed the same (small objects) or reduced (large objects). The scaling 'stretches' the observed size of the object, and thus of the target area, reducing the perceived difficulty of the target and thus making it easier to hit.

Mean absolute jerk normalised by peak speed

The variable gain controller shows a significant improvement over the proportional gain controller across the entire range of motion, which seems to indicate that the human shoulder can execute larger movements much smoother than smaller ones. Allowing the user to use a larger motion for fine positioning thus results in a smoother, more controlled motion.

5.2 Conclusion for metrics

Based on the metrics, using a variable gain is preferred to using a proportional gain, since performance either remains the same or improves for task performance. The increased fine positioning time for small objects indicates a shift from speed to accuracy as designed, and is compensated for by the increased speed over the gross positioning which indicates no overall loss in performance anywhere on the range of motion. The controller performance is significantly better as well.

5.3 Limitations and future work

The virtual slave and -environment allow for all variables to be perfectly constant and thus allow for a perfect comparison of the dependent variables - as long as the signals are within the virtual environment. Sensors and actuators are never perfect and neither is the environment the device is supposed to be used in. This experiment offers an abstract task in an abstract, simplified representation of reality to check for significant differences between modes of control in a speed-precision task, which is then executed by the subject using the same sort of harness a body powered prosthesis would use. What this experiment shows is the behaviour of the human shoulders when met with different types of control schemes, so see what the major differences are. Now that is established that a variable gain in a system like this could be viable, this model has to be refined, made adaptable to individual users and built into a real-world prototype to see if this theoretical benefit would hold up in the physical world.

An important limitation that has to be noted is the absence of gravity in this experiment. Heavier objects require higher grasp force to be held, but this would require a method to apply a weight to the subject that would only be applied when the subject 'lifts' the weight after grasping. It would require additional hardware and make the experiment more complicated, which is why grasping and squeezing was chosen for this experiment rather than grasping and lifting.

Feedback from subjects showed one more important piece of information: Preferences differ widely from person to person. All three controllers were loved by some users, detested by others. The controllers behaved very differently, based purely on the software model running at that instant. If fitting prostheses to their users' preferences becomes more and more a software problem, the hardware could become more and more standardised - and thus cheaper. changing the force- or position gains could assist weaker users or could be changed gradually to increase strength and mobility in their users, or even monitor performance in real time and adjust gains to compensate for fatigue. Users could use different profiles to initiate different types of controllers, based on the task they are doing. It could even be possible to use a neural network to keep improving performance, based on the collective data of users. The main takeaway is that the versatility of a system with a software model at its core that mimics a cable operated device opens up a lot of possibilities for adapting a system to the individual needs of the users while maintaining the benefits of the intuitive nature of these low-tech devices.

6 CONCLUSION

Workspace extension can be used to design a controller which improves the overall performance for a shoulder shrug controlled, by-wire operated grasping prosthesis without sacrificing performance in part of the range of motion, but the importance of a clear position-to-position and velocity-to-velocity relationship between the master- and slave devices is insightful, as it outperformed velocity control to the point where it could not be considered a viable mode of control for this task. The non-linear, variable gain designed to increase the part of the range of motion used to grasp an object by speeding up while no object has been grasped yet was proven to be a promising method.

Another find was that no matter the individual performance, the rate of grasping time between a large and a small object remains the same. This signifies that performance is constant over the entire range of motion.

7 ACKNOWLEDGEMENTS

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REFERENCES

[1] D. S. Childress, 'Closed-Loop Control in Prosthetic Systems: Historical Perspective', Annals of Biomedical Engineering, Volume 9, Pages 293-303, 1980.

[2] D. S. Childress, "Upper-Limb Prosthetics: Control of Limb Prostheses", in, Atlas of Limb Prosthetics: Surgical, Prosthetic, and Rehabilitation Principles, J. H. Bowker, Mosby Inc, 1992

[3] I. Dudkiewicz, R. Gabrielov, I. Seiv-Ner, G. Zelig and M. Heim, 'Evaluation of prosthetic usage in upper limb amputees', Disability and Rehabilitation, Volume 26, No.1, Pages 60-63, 2004.

[4] Farrell TR, Weir RF, Heckathorne CW, Childress DS. The effects of static friction and backlash on extended physiological proprioception control of a powered prosthesis. J Rehabil Res Dev. 2005;42(3):327–41

[5] E. A. Biddiss and T. T. Chau, 'Upper limb prosthesis use and abandonment: A survey of the last 25 years', Prosthetics and Orthotics International, Volume 31, No. 3, Pages 236-257, 2007.

[6] E.F. Murphy, "In Support of the Hook", Clinical Prosthetics and Orthotics, Volume 10, No. 2, pp. 78-81, 1986

[7] D.H. Plettenburg, M. Hichert, G. Smit, "Feedback in Voluntary Closing Arm Prostheses: Inverstigation of optimal force feedback in shoulder controlled arm prosthesis operation", "MEC raising the Standard," Proceedings of the 2011 MyoElectric Controls/Powered Prosthetics Symposium Fredericton, New Brunswick, Canada: August 14-19, 2011

[8] D.H. Plettenburg, "Upper extremity prosthetics. Current status and evaluation" VSSD, Delft, ISBN 9789071301759, 2006

[9] E.A. Biddiss,. T. Chau, "Electroactive polymeric sensors in hand prostheses: bending response of an ionic polymer metal composite." Medical Engineering & Physics, Vol. 28, pp. 568-78, 2006

[10] D.C. Simpson, "The choice of control system for multimovement prosthesis: extended physiological proprioception (e.p.p.)." In: Herberts .P. (ed.) The control of upper extremity prostheses and orthoses. Thomas, Springfield, Ill. pp. 146-150, 1974

[11] Weir RF, Heckathorne CW, Childress DS. Cineplasty as a control input for externally powered prosthetic components. J Rehabil Res Dev. 2001;38(4):357–63. [PMID:11563487]

[12] Pylatiuk C, Kargov A, Schulz S. Design and evaluation of a low-cost force feedback system for myoelectric prosthetic hands. J Prosthet Orthot. 2006;18:57–61.

[13] K. A. Farry, I. D. Walker, R. G. Baraniuk, 'Myoelectric teleoperation of a complex robotic hand', IEEE Transactions on Robotics and Automation, Vol- volume 12, No. 5, Pages 775-788, 1996.

[14] S. Nambu et al., "Advantages of externally powered prosthesis with feedback system using pseudo-cineplasy", Journal of Rehabilitation Research & Development, Volume 51, No. 7, Pages 1095-1102, 2014.

[15] R. Van der Klauw, "A design method for Variable Rotational Workspace Extension applied to Telemanipulation Tasks", M. S. Thesis, Delft University of Technology, Delft, Netherlands, 2017.

[16] D. McRuer and H. Jex, "A Review of Quasi-Linear Pilot Models", Transactions on human factors in electronics, Vol. 8, No. 3, 1967.

[17] W. Buxton, in There's More to Interaction than Meets the Eye: Some Issues in Manual Input, Hillsdale, New Jersey, Lawrence Erlbaum Associates, pp. 319-337, 1986.

[18] I. Poupyrev, S. Weghorst and S. Fels, "Non-Isomorphic 3D Rotational Techniques", Human factors in computing systems, pp. 240-547, 2000.

[19] P. Fitts, "The information capacity of the human motor system in controlling the amplitude of movement", Journal of experimental psychology, Vol. 47, pp. 381-391, 1954.

[20] N. Hogan and D. Sternad, "Sensitivity of Smoothness Measures to Movement Duration, Amplitude and Arrests", Journal of Motor Behaviour, Vol. 41, No. 6, pp. 529-534, 2009.

[21] J.A. Doubler, D.S. Childress, "An Analysis of Extended Physiological Proprioception as a Prosthesis Control Technique", Journal of Rehabilitation Research & Development, Vol. 21, No. 1, pp. 5-18, 1984.

[22] J.A. Doubler, D.S. Childress, "Design and Evaluation of a Prosthesis Control System based on the Concept of Extended Physiological Proprioception", Journal of Rehabilitation Research & Development, Vol. 21, No. 1, pp. 19-31, 1984.

APPENDICES

Appendix 1: Raw data
Overview of raw data for each subject

Appendix 2: Participant Information
Instructions and information as provided during the experiment

Appendix 3: Informed Consent
Informed consent as signed by the participants

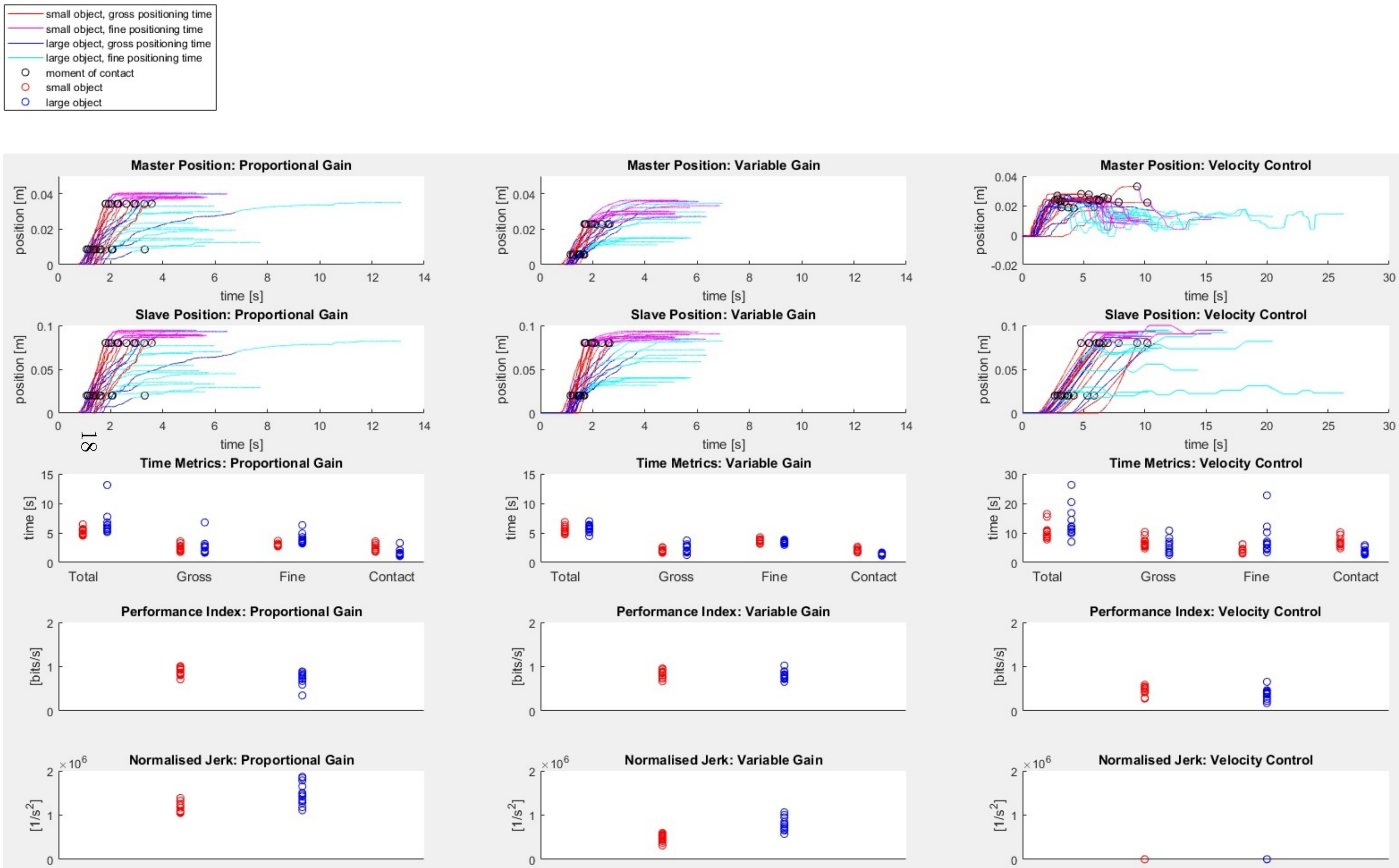
Appendix 4: Device Report
Device report accepted by the TU Delft Human Research Safety Committee

Appendix 5: Checklist Ethics Committee
Checklist provided to the TU Delft Human Research Ethics Committee

Appendix 6: Letter of Approval
Letter of Approval for experiment by the TU Delft Human Research Ethics Committee

Appendix 7: Wiring Description
Wiring description used to install the Bachmann real time computer into the experimental setup

Due to availability, an AIO216 module was used instead of an AIO288 module. This required the following changes in wiring:
In section 3.1 (Emergency button): on the AIO module, connect the positive wire to port 12 and the negative wire to port 14 (instead of to ports 14 and 15, respectively).
In section 3.3 (Futek): on the AIO module, connect the positive wire to port 7, the negative wire to port 8 and the ground wire to port 10 (instead of positive to port 9 and negative to ports 10 and 11 (ground)).
In section 3.4 (LVDT): on the AIO module, connect the positive wire to port 2, the negative wire to port 3 and the ground wire to port 5 (instead of positive to port 2 and negative to ports 3 and 4 (ground)).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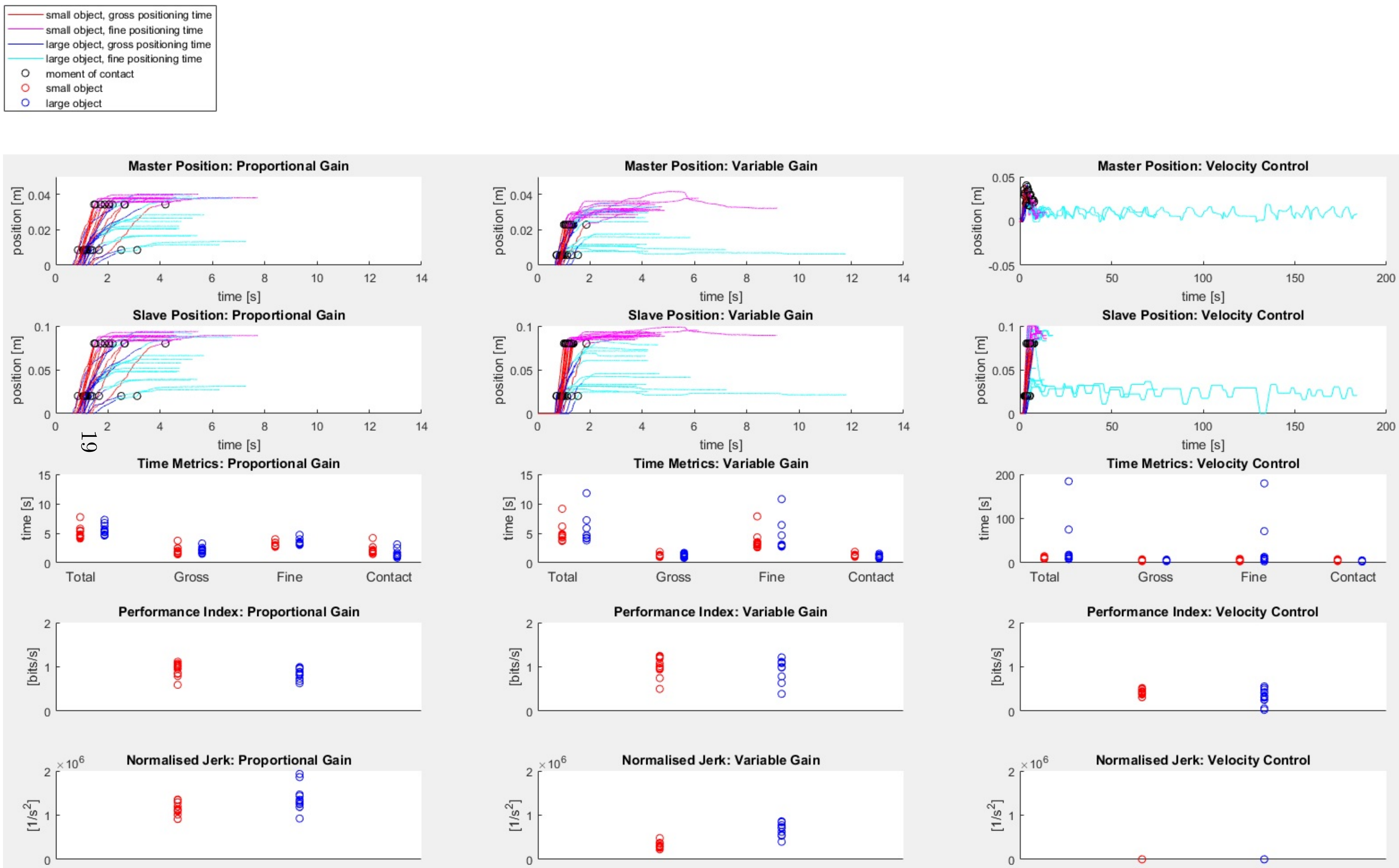
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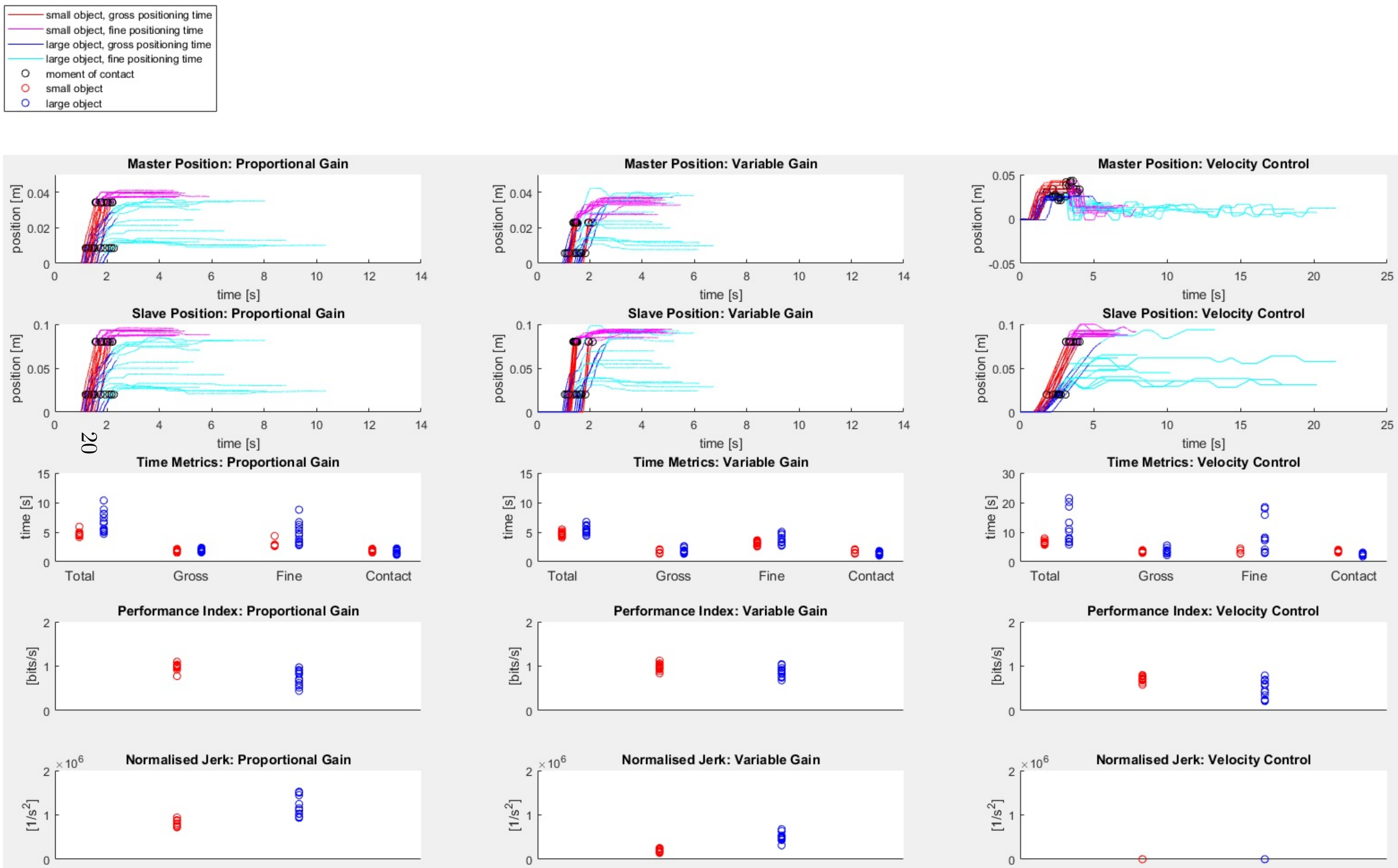
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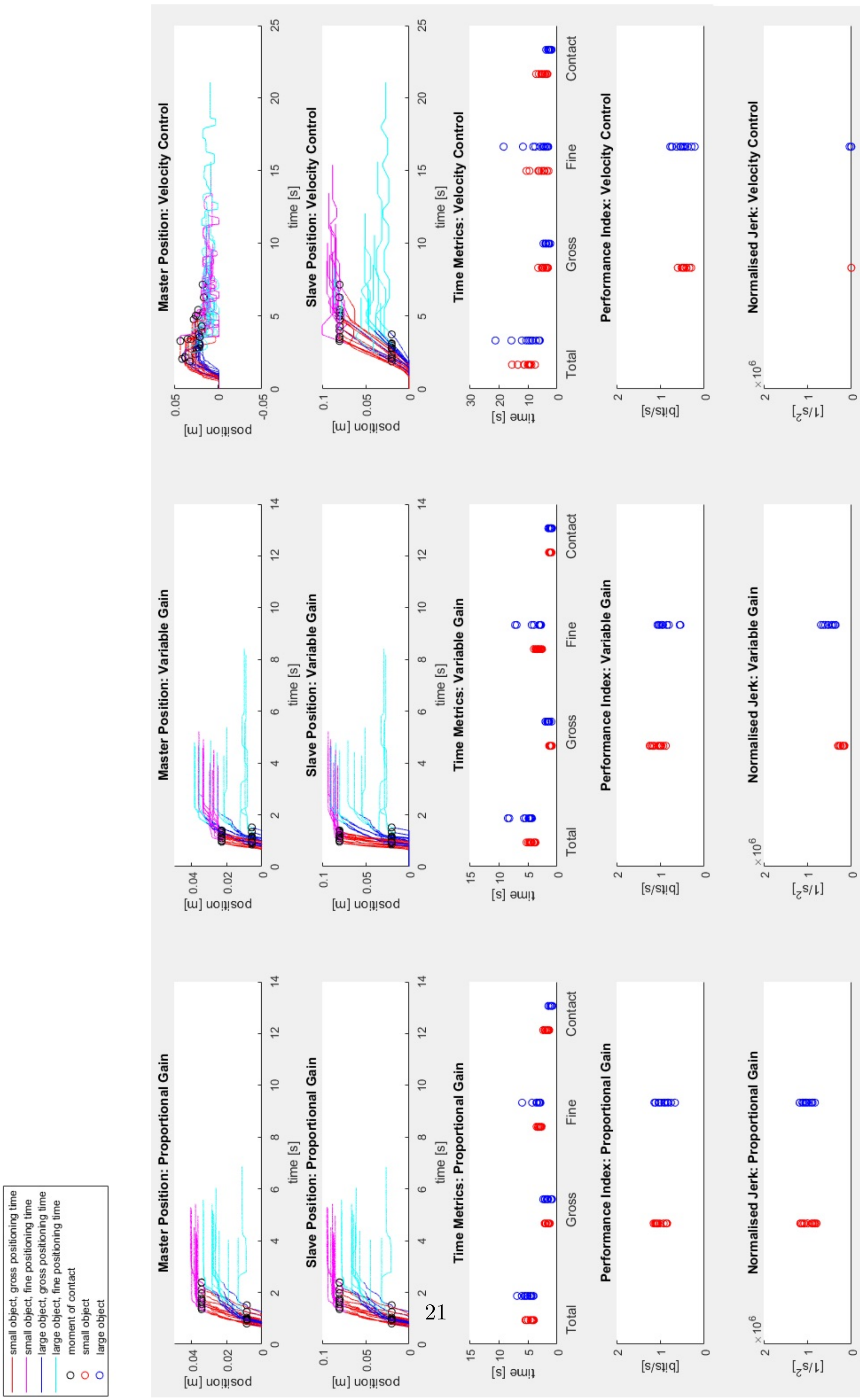

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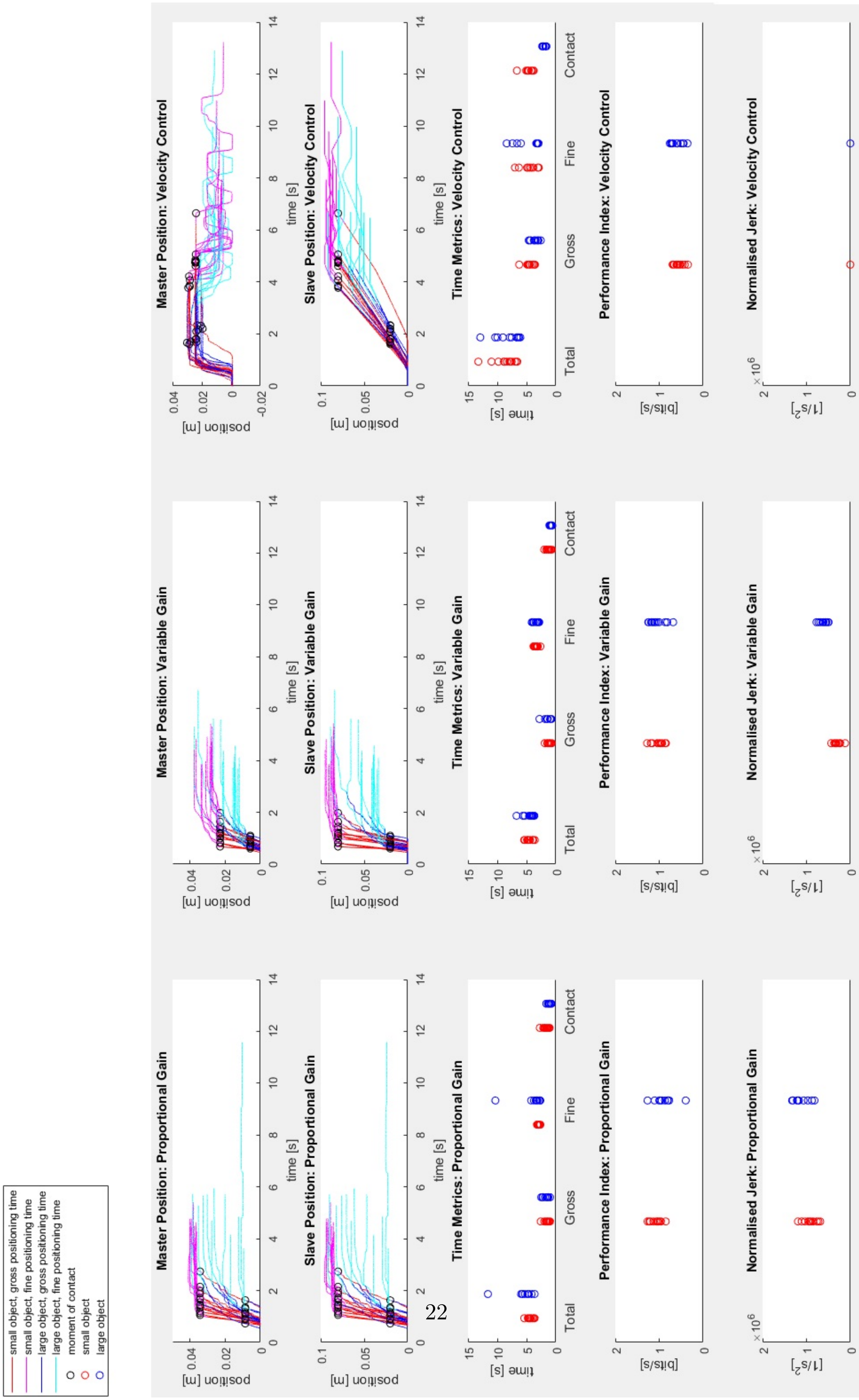
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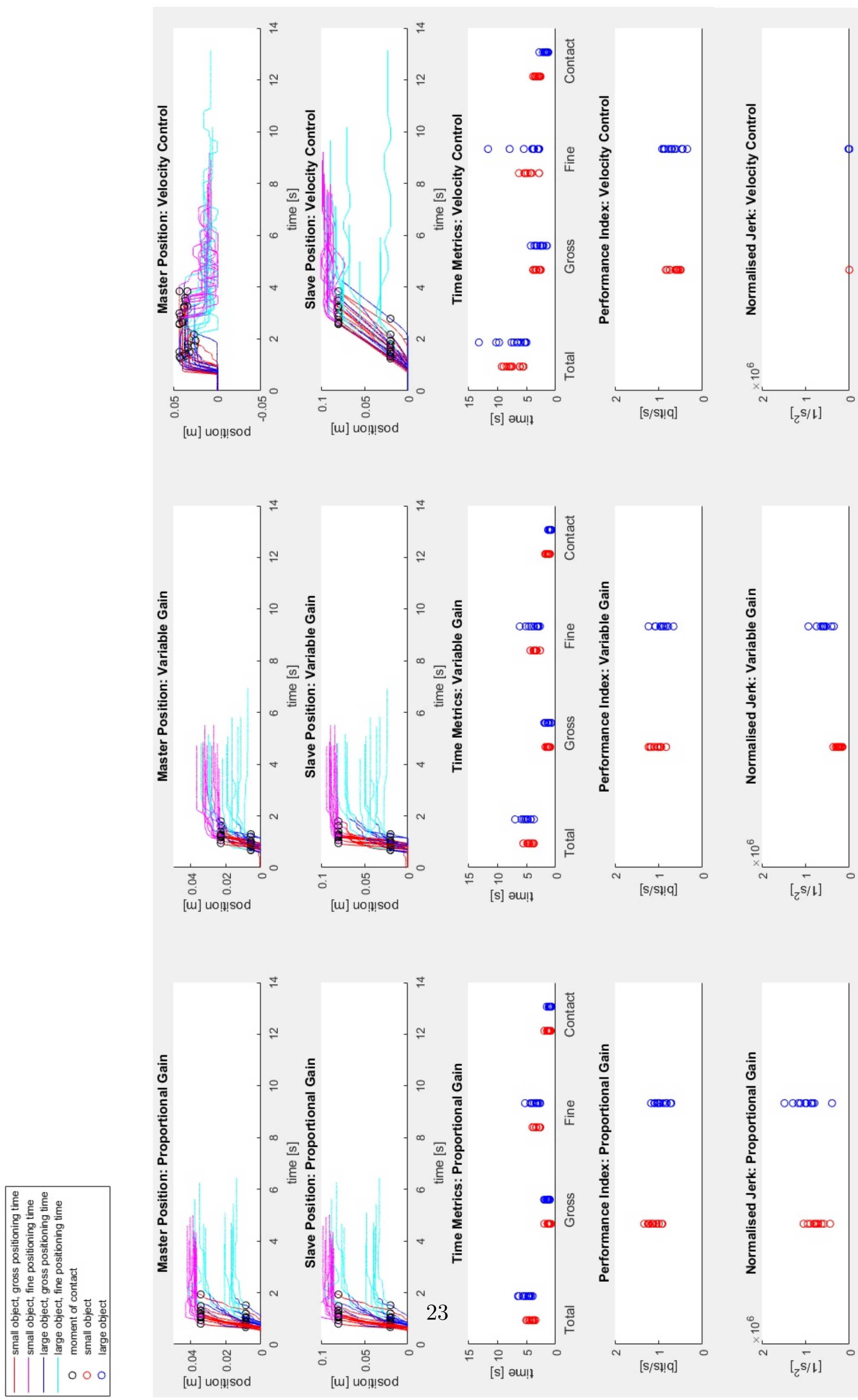
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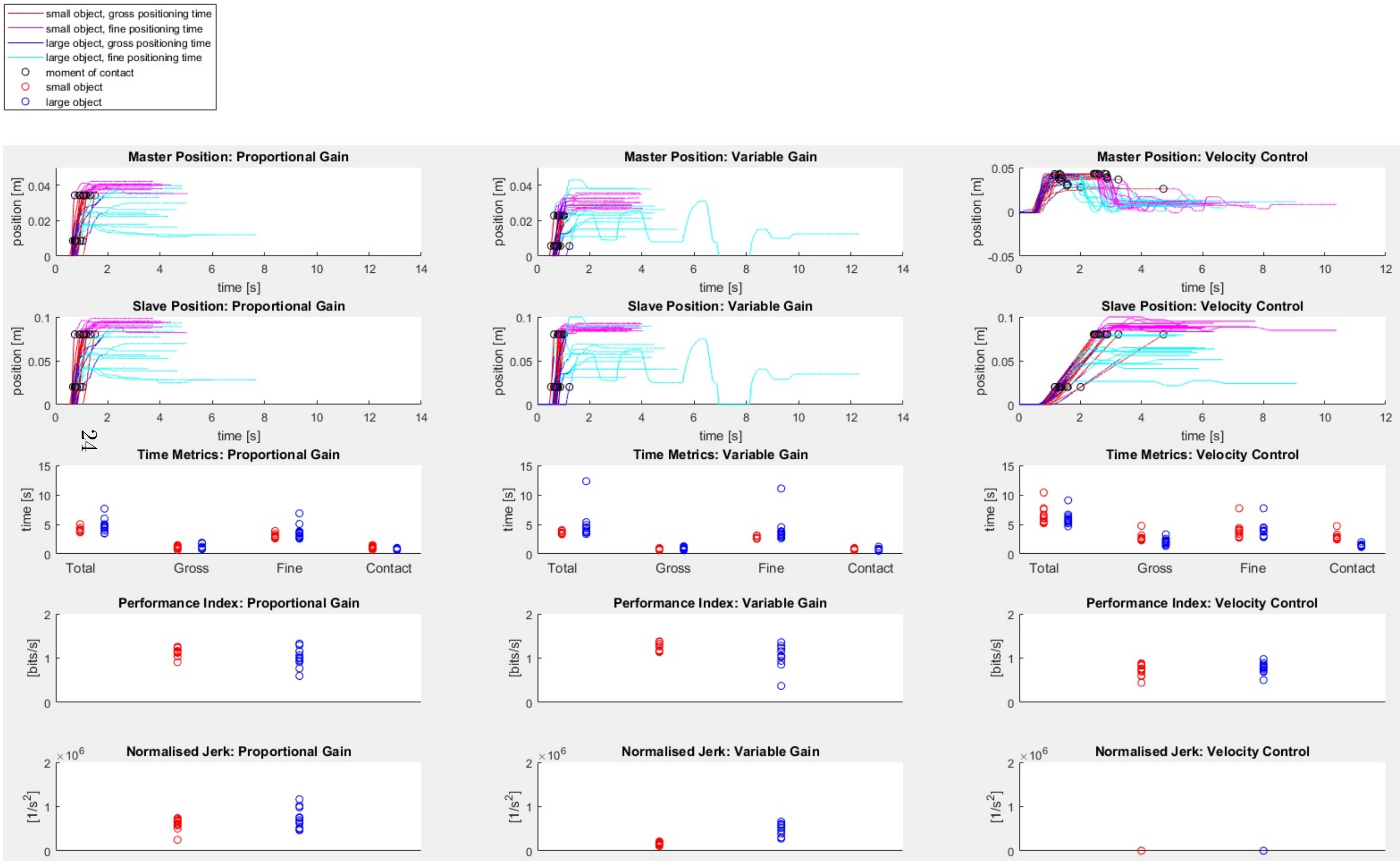

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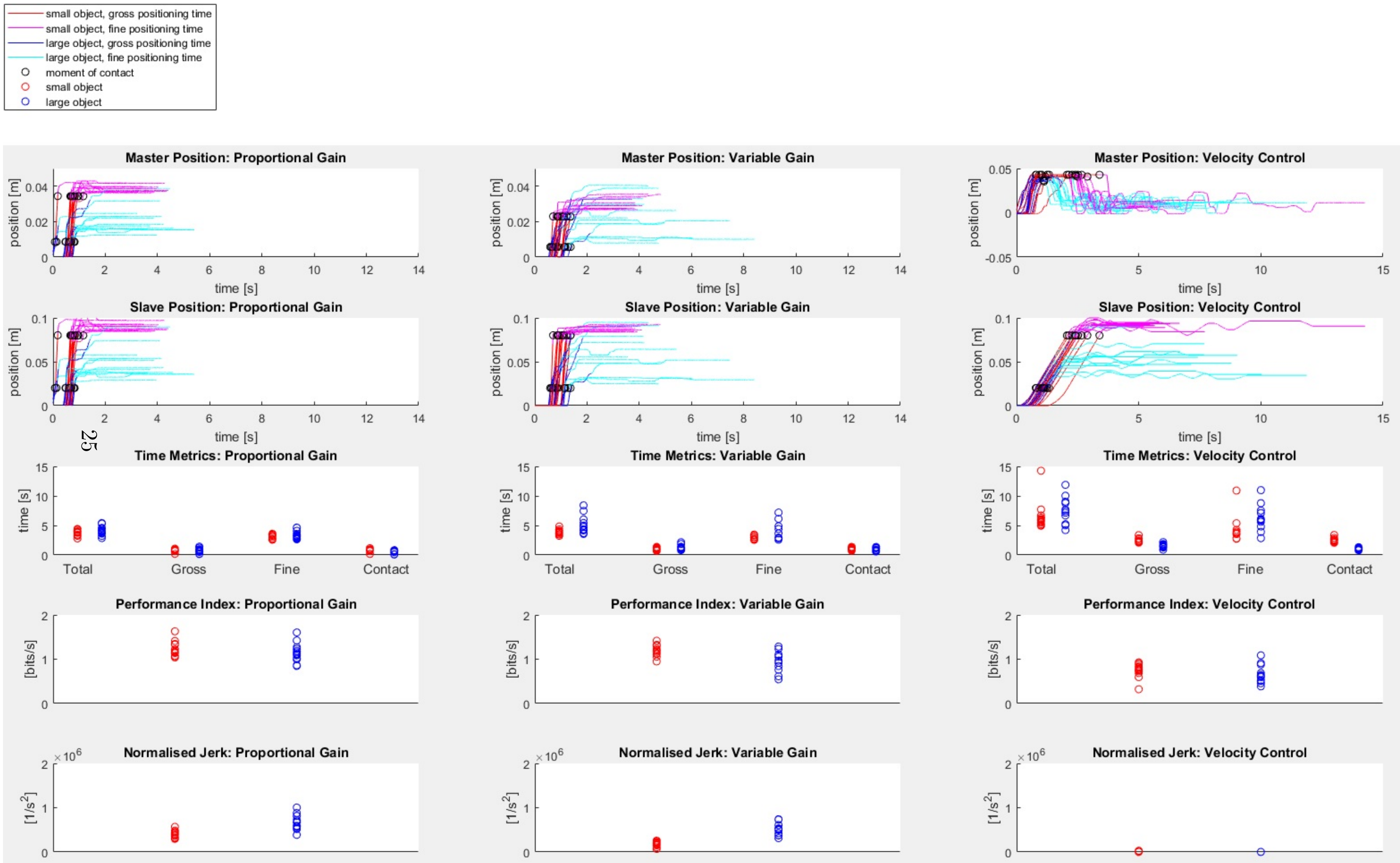

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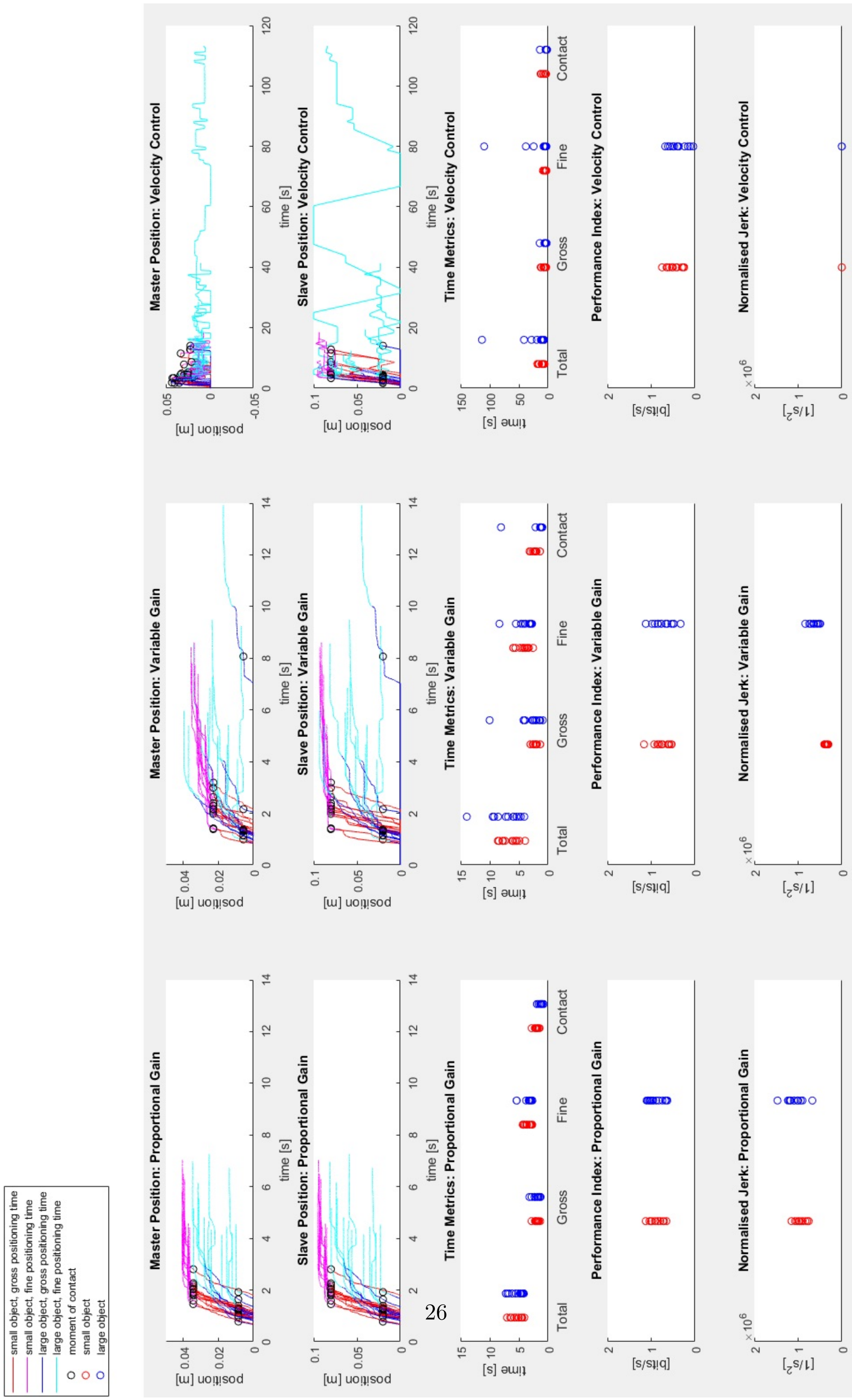
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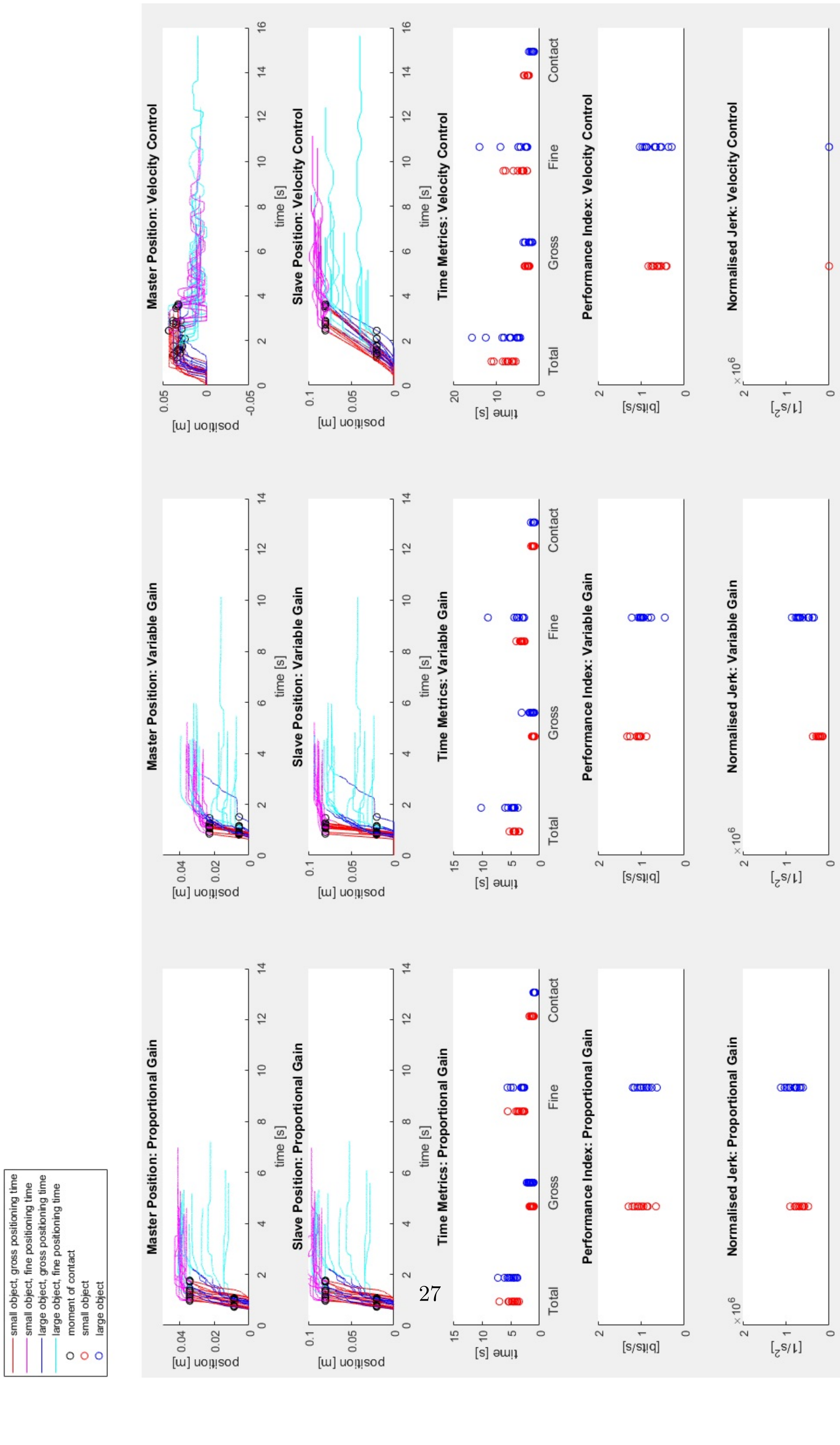
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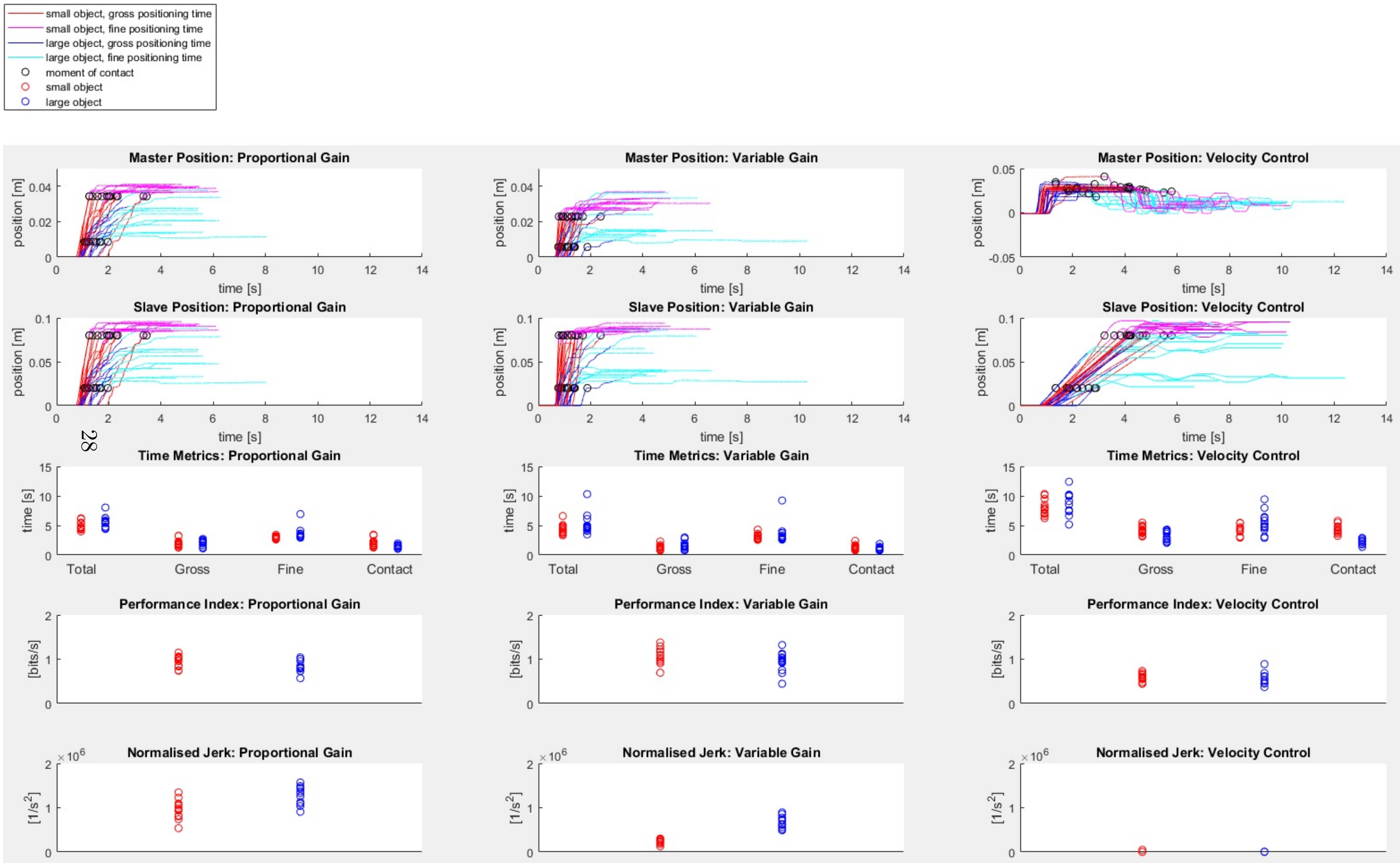

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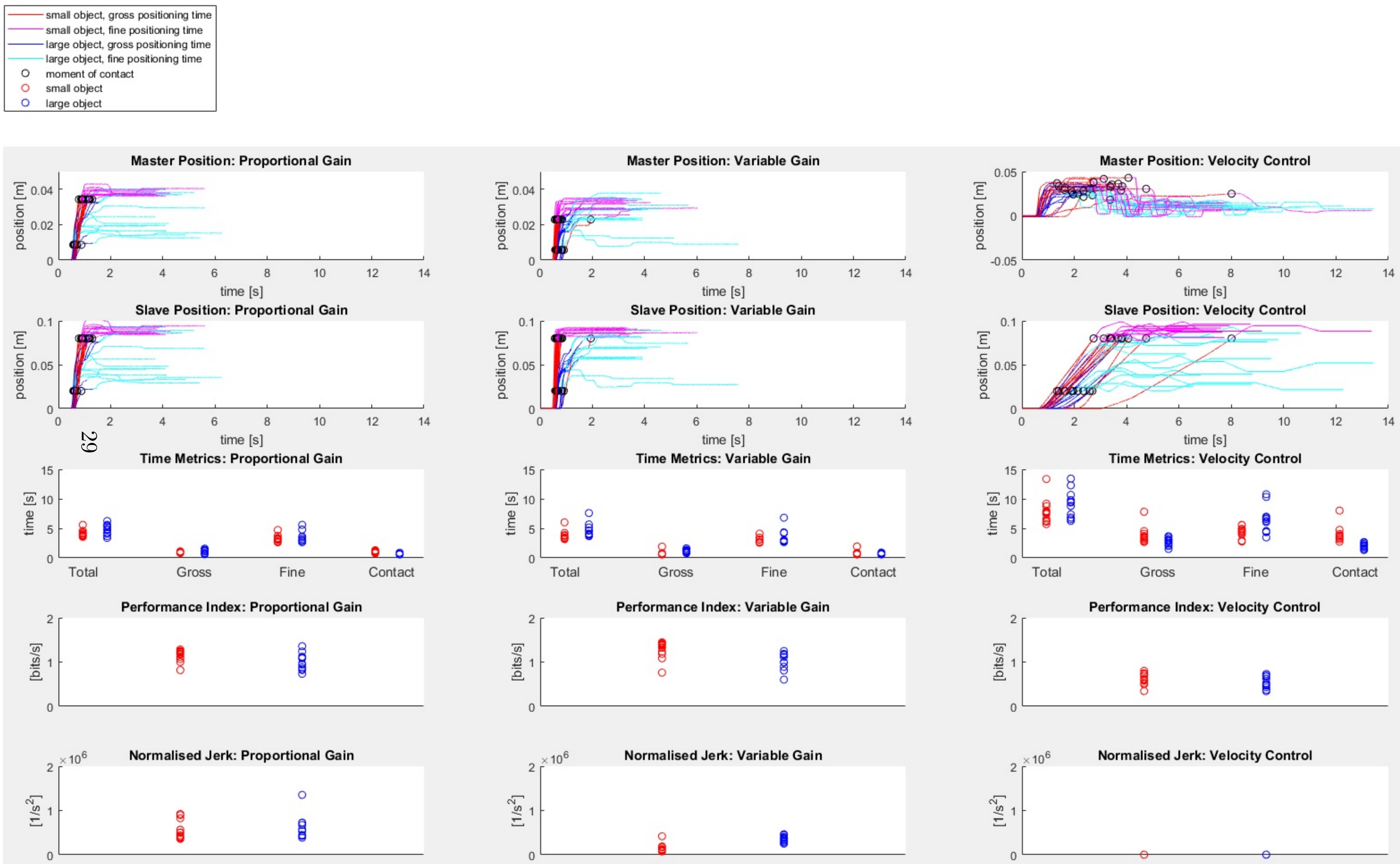
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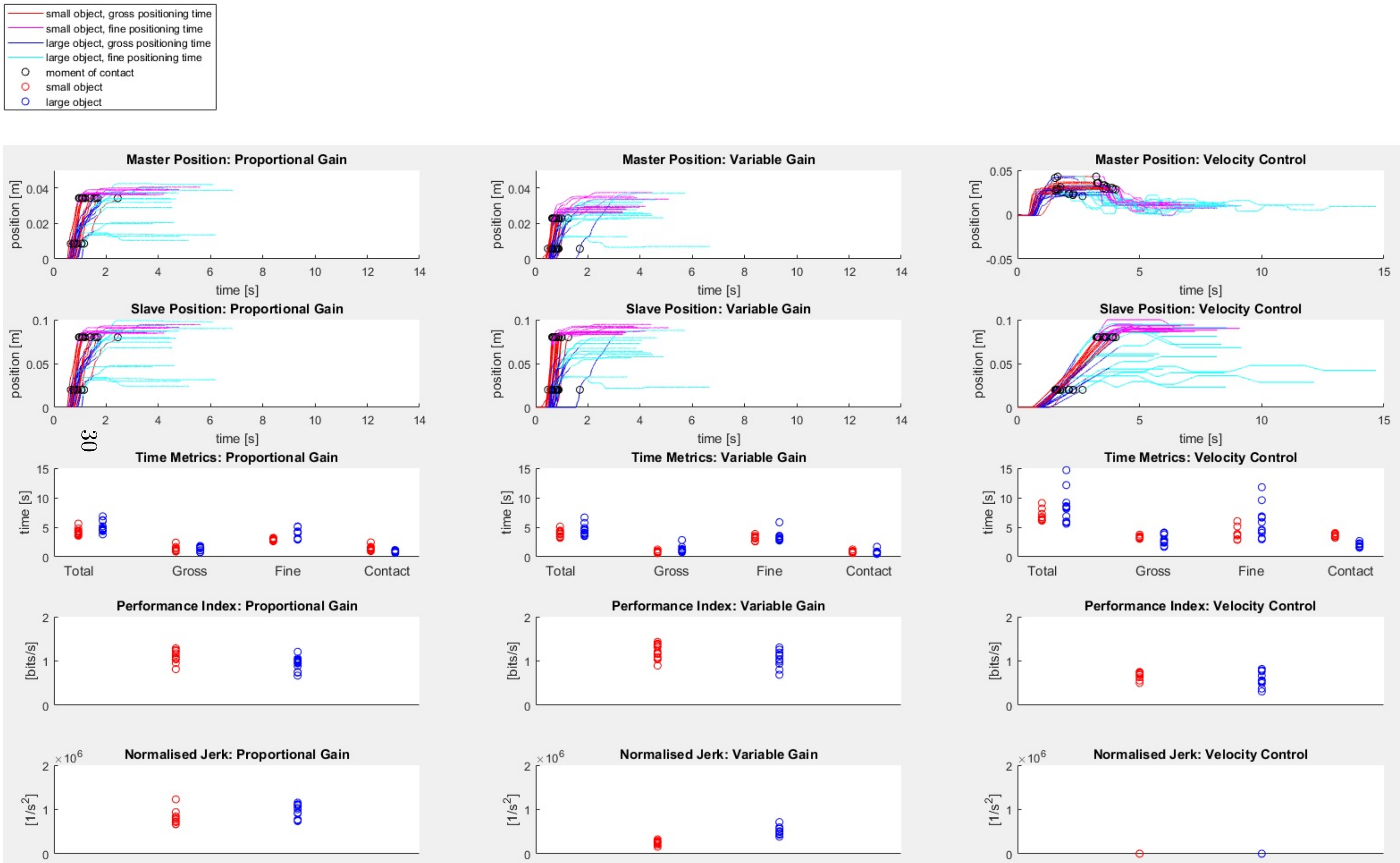
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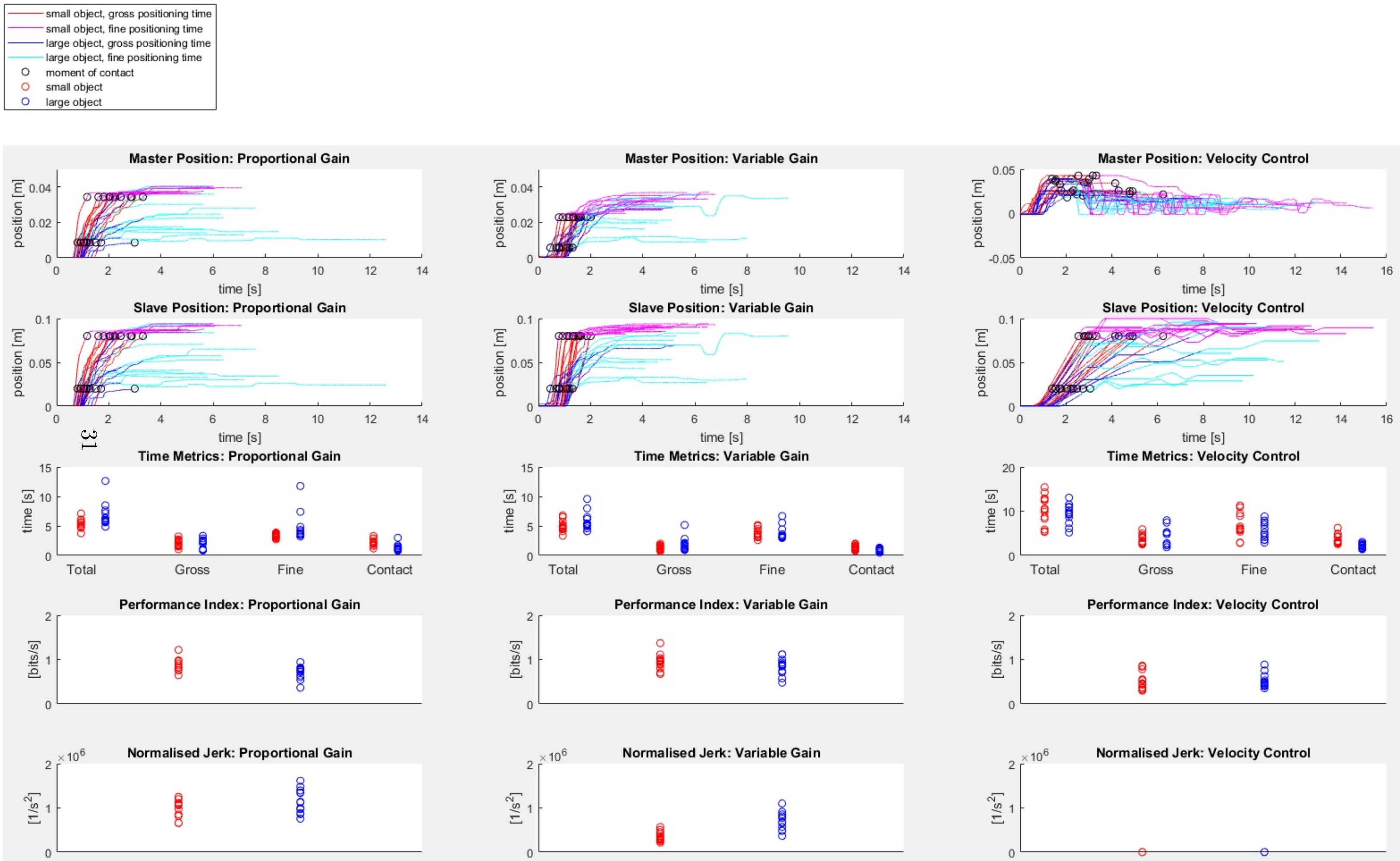
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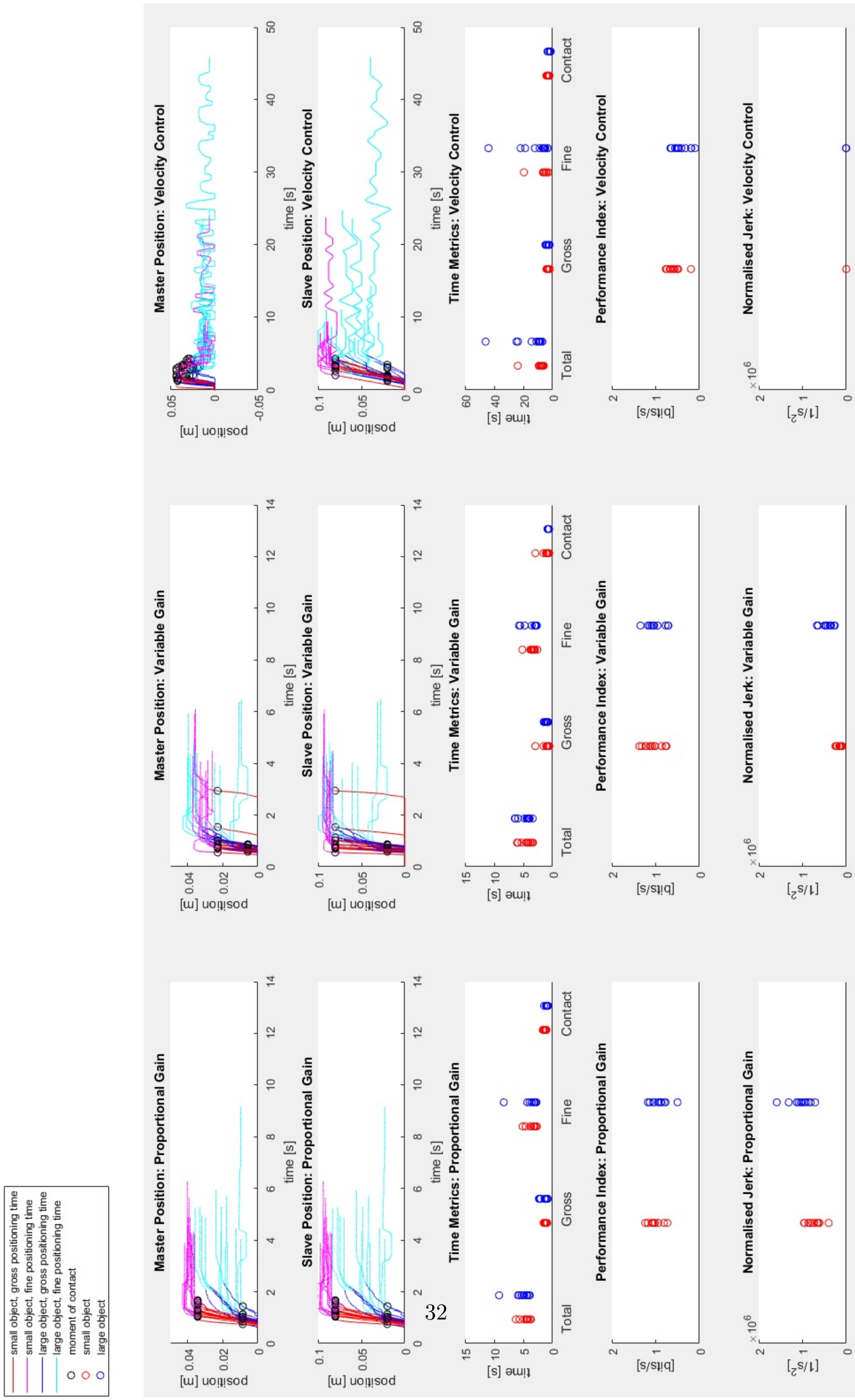
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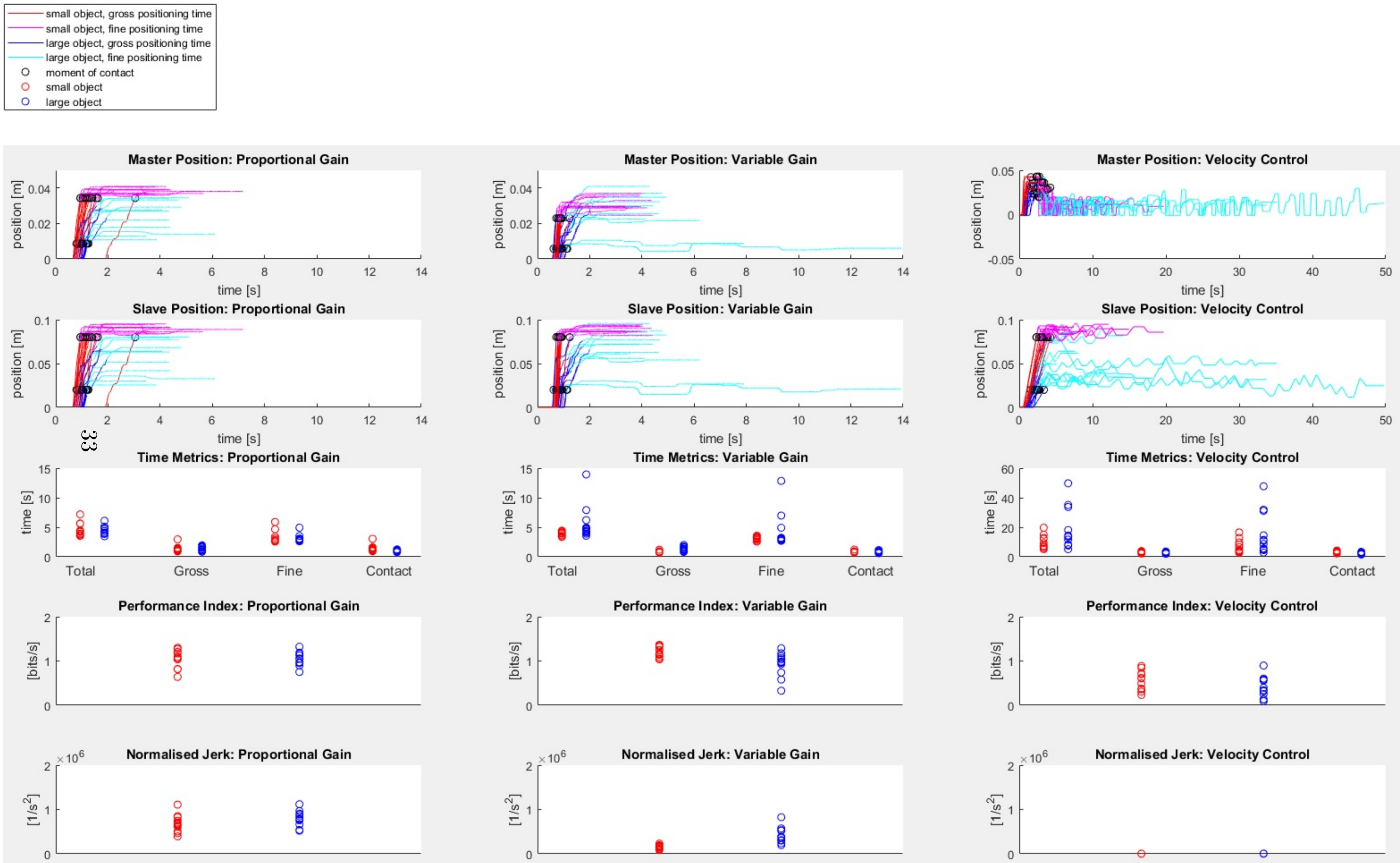
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Time Metrics: Variable Gain
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Performance Index: Proportional Gain
Performance Index: Variable Gain
Performance Index: Velocity Control
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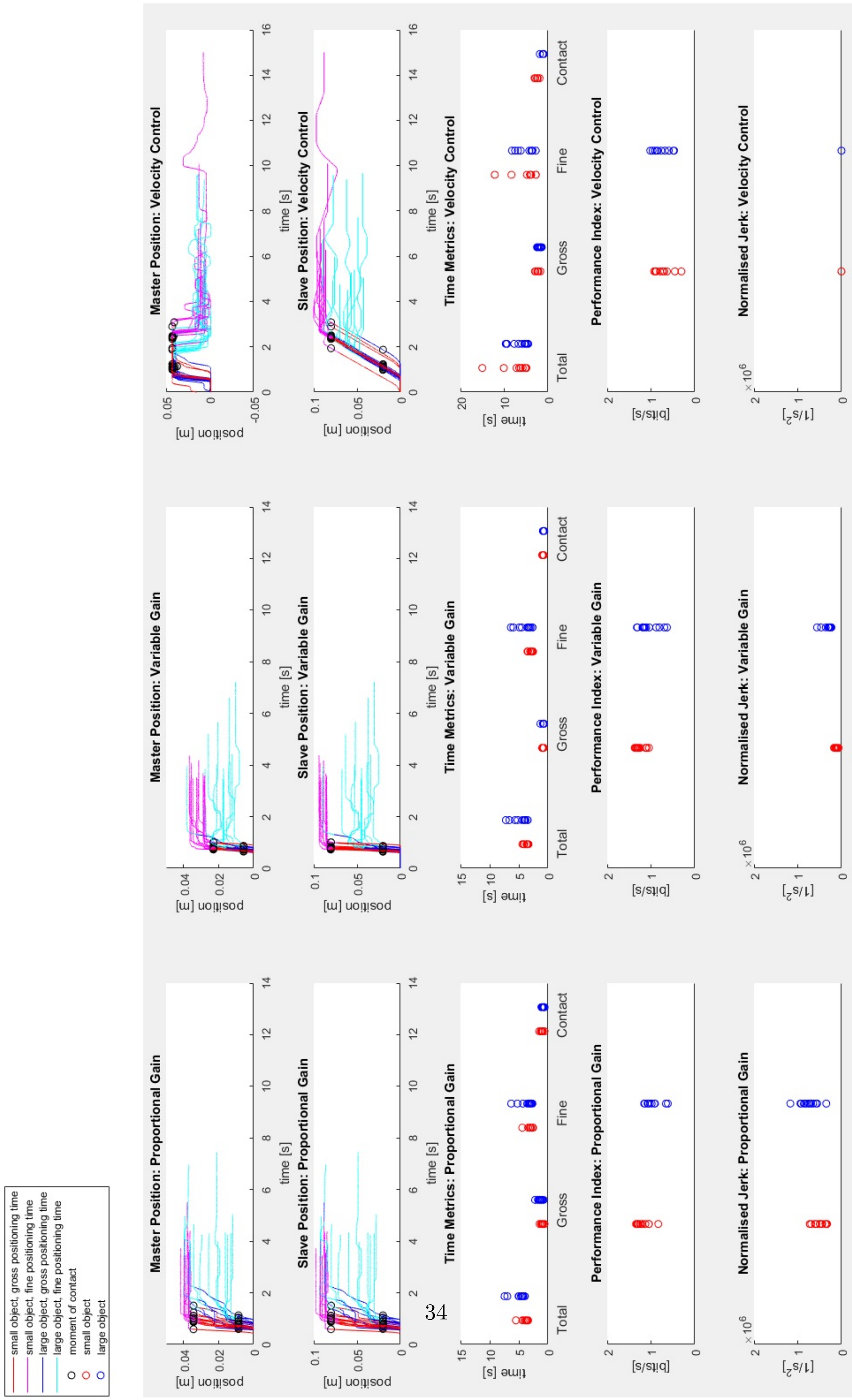
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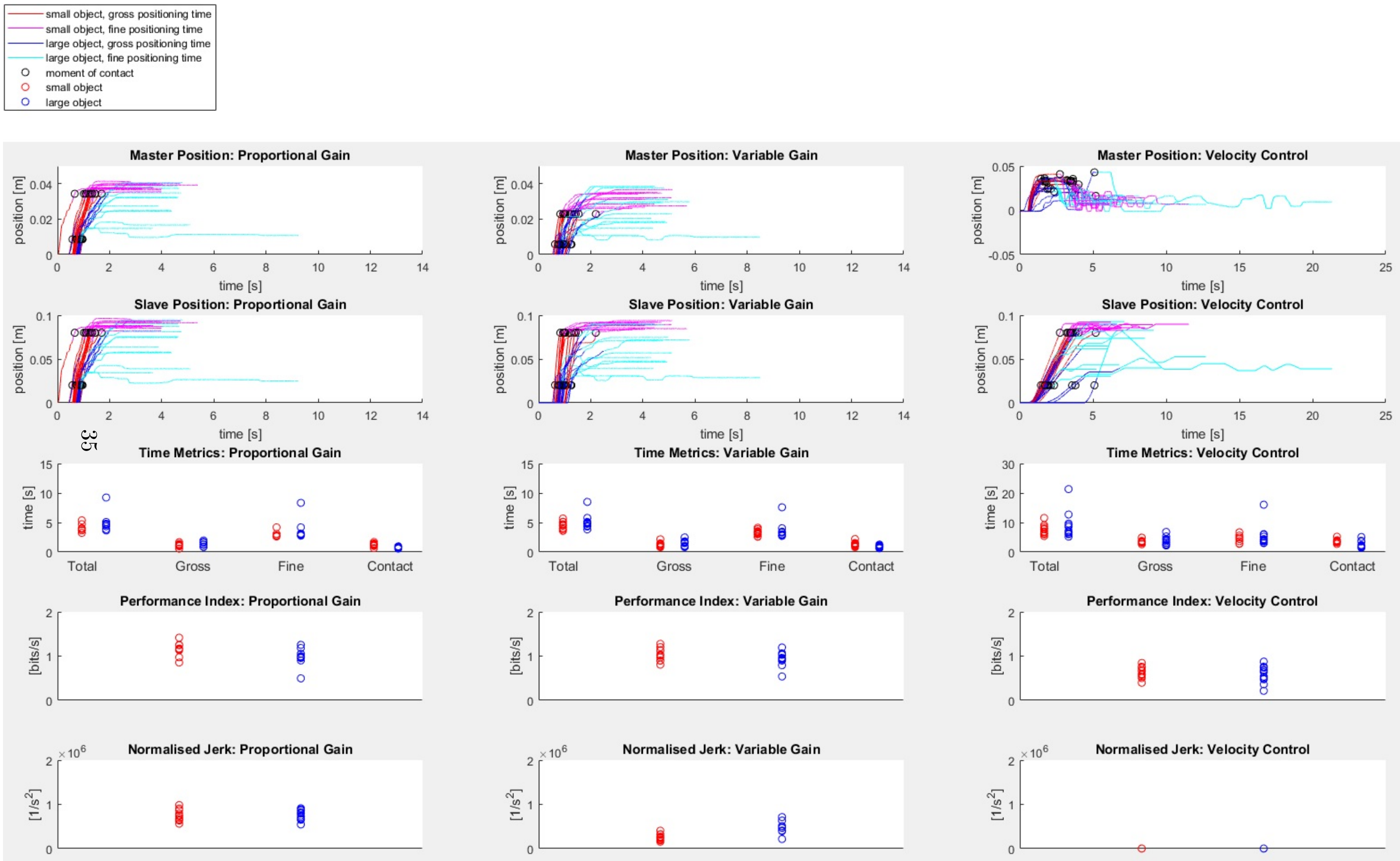

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Performance Index: Velocity Control
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Normalised Jerk: Proportional Gain
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Normalised Jerk: Velocity Control
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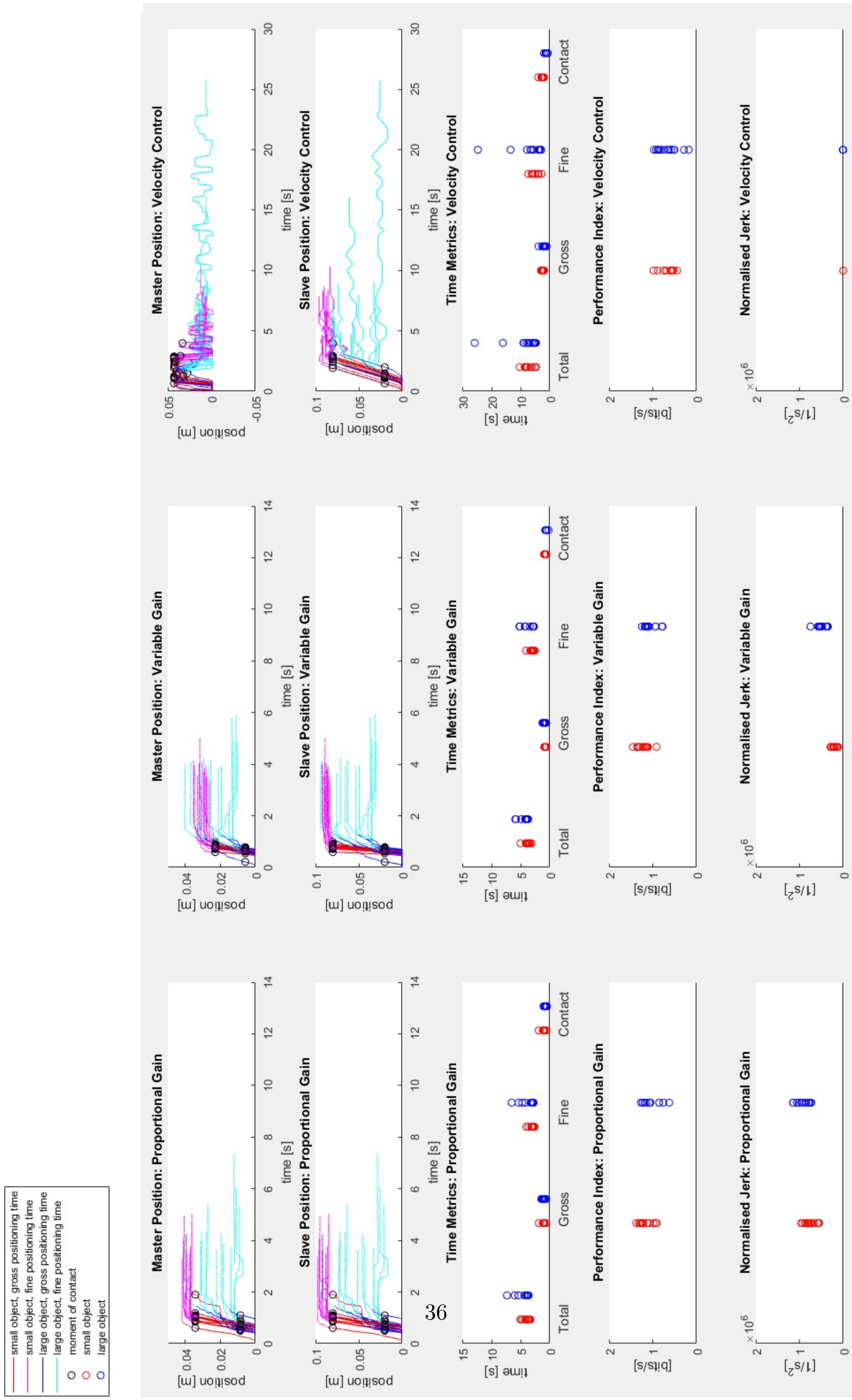
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Master Position: Variable Gain
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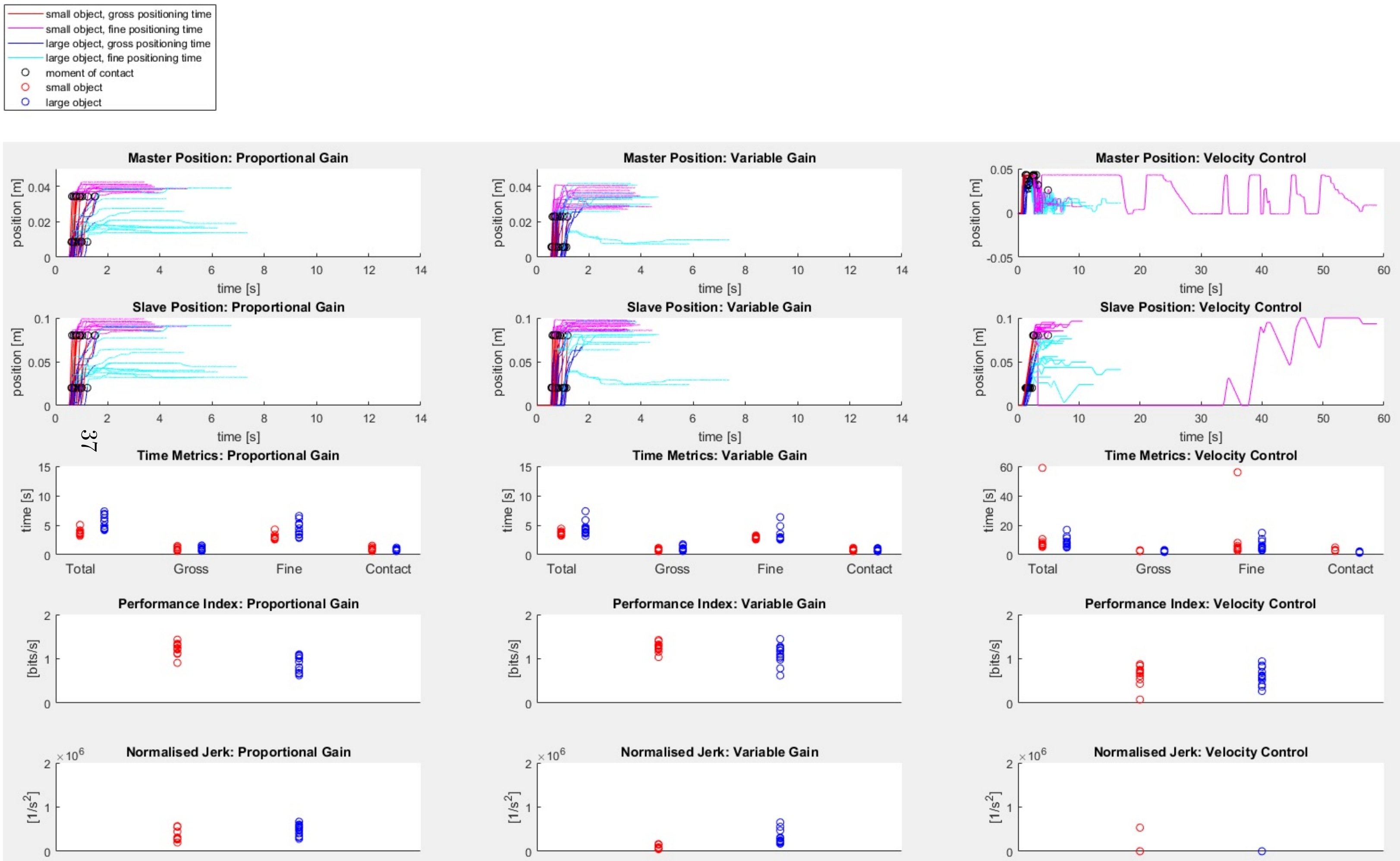
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time [s]
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Performance Index: Proportional Gain
Performance Index: Variable Gain
Performance Index: Velocity Control
[bits/s]
Normalised Jerk: Proportional Gain
Normalised Jerk: Variable Gain
Normalised Jerk: Velocity Control
[1/s²]
×10⁶

Cognitive Robotics Laboratory

DEELNEMER INFORMATIEBRIEF

Betreffende het onderzoek naar de effecten van schaling in prothese-aansturing via by-wire master-slave systeem.

Datum 06-12-2018, Versie 1.0

Geachte mevrouw/meneer,

U bent gevraagd mee te werken aan een onderzoek waarin we het effect van schaling op een elektronische koppeling tussen schouders en prothese bestuderen. In deze brief vindt u uitgebreide informatie over het onderzoek. Mocht u nog vragen hebben, dan kunt u terecht bij de personen die onderaan de brief zijn vermeld.

Achtergrond van het onderzoek

Actieve armprothesen, met bewegende delen die de taken van het verloren ledemaat (deels) overnemen, zijn te verdelen in twee hoofdgroepen: aangestuurd door lichaamskracht of aangestuurd door een externe krachtbron. De eerste soort gebruikt de beweging van een ander lichaamsdeel, meestal de schouders of de elleboog, om een kabel aan te trekken die de 'hand' bedient. Omdat dit werktuig als een verlengstuk van het lichaam wordt gebruikt, is het een intuïtieve manier van bedienen; net zoals men bij een tang aan het handvat voelt hoeveel kracht de tang uitoefent, voelt men bij dit soort prothesen met hoe veel kracht er geknepen wordt. Het nadeel is dat er erg veel kracht verloren gaat, waardoor de kracht door de gebruiker vele malen groter kan zijn dan de kracht die op het gegrepen object wordt uitgeoefend en gebruik op de lange termijn erg vermoeiend kan zijn. Een onacceptabel groot deel van deze prothesen eindigt om deze reden ongebruikt in de kast.

Extern aangestuude prothesen werken door de elektrische stroom te meten die door de spieren loopt wanneer deze worden aangespannen. Hierdoor kan de prothese worden aangestuurd met een relatief lage inspanning, terwijl de krachten aan de 'hand' veel groter kunnen zijn. Het nadeel is dat er geen fysieke connectie is waarmee het lichaam kan voelen hoeveel kracht wordt uitgeoefend.

Bij een by-wire connectie worden positie en kracht omgezet in elektrische signalen die door middel van elektromotoren worden uitgeoefend. Op deze manier voelt het alsof er een fysieke connectie is, maar omdat die er niet echt is kan dit signaal worden aangepast om de gebruiker te helpen. Zo kunnen de voordelen van lichaamsaangestuurde en extern aangestuurde systemen worden gecombineerd. Dit soort schaling noemen we 'workspace extension'. Het onderzoek bekijkt hoe verschillende soorten schaling de precisie en gemak waarmee de gebruiker de prothese aanstuurt beïnvloeden.

Doel van het onderzoek

De krachten die worden ondervonden door de gebruiker tijdens dit onderzoek zijn vele malen lager dan bij conventionele lichaamsaangestuurde prothesen, maar vallen binnen de aanbevolen krachtniveaus voor gebruikers die een ledemaat missen (Plettenburg et al., 2011). Het doel van het onderzoek is te bekijken welke soort schaling het beste kan worden toegepast binnen deze situatie om beter gebruik te kunnen maken van dit krachtspectrum.

Wat houdt deelname aan het onderzoek in?

Om het schouderharnas aan te sluiten worden twee connectoren met dubbelzijdig- of sporttape op de huid over uw schouderbladen bevestigd. Deze connectoren houden de geleidende buitenkabel en de actieve binnenkabel op hun plek. Dit houdt wel in dat u dit experiment met ontbloot bovenlijf zult uitvoeren. Hierom is een een afgeschermde ruimte beschikbaar waar alleen u en de proefleider aanwezig zullen zijn. De binnenkabel is verbonden met het masterdevice, dat de positie van uw schouders vertaalt naar elektrische signalen en u voorziet van feedback in de vorm van krachten. Het slavedevice is virtueel en wordt weergegeven op het beeldscherm.

Het experiment omvat 75 trials, waarvan 15 oefentrials. U zult drie soorten controllers, elk met hun eigen schaling, gebruiken om een zacht voorwerp vast te pakken en in te knijpen tot de bewegende kant van de virtuele prothese binnen de groene target valt. De volgorde waarin de controllers worden aangeboden is verschillend, om leereffecten van omgaan met het harnas op de data te elimineren. De controllers zijn een lineair model (geen schaling) als controle, een variabele schaling, en een snelheidscontroller (de positie van de schouders bepaalt de snelheid waarmee de slave beweegt). Het onderzoek neemt ongeveer een halfuur in beslag.

Het onderzoek vindt plaats in het Laboratorium voor Cognitive Robotics in faculteit 3ME van de TU Delft.

Risico's

De risico's van de metingen zijn klein. De beweging van manipulator is beveiligd tegen te grote bewegingen en te grote of plotselinge krachten. Vóór deelname aan het onderzoek wordt door de onderzoeker een inschatting gemaakt of u in staat bent het onderzoek te voltooien. De apparatuur bevat een hoog- en een laagspanning circuit en een aantal bewegende onderdelen. Deze zijn afgeschermd en/of buiten direct bereik geplaatst. Voor uw eigen veiligheid mag u de apparatuur op de tafel absoluut niet aanraken.

Vrijwillige deelname

Uw medewerking aan dit onderzoek is vrijwillig. Als u toestemming geeft aan dit onderzoek mee te doen heeft u te allen tijde (ook tijdens het onderzoek) de vrijheid om op die beslissing terug te komen. U hoeft hiervoor geen verklaring te geven.
Als u bereid bent aan het onderzoek mee te doen, zal ter plekke een toestemmingsformulier worden voorgelegd.

Vertrouwelijkheid gegevens en betekenis van het onderzoek

We zullen vertrouwelijk met uw persoonlijke gegevens omgaan. Wij zullen ervoor zorgen dat niet-bevoegde buitenstaanders geen inzage hebben in uw persoonlijke gegevens. Wanneer de resultaten van het onderzoek gepubliceerd worden, zal informatie niet op u terug te herleiden zijn.

Samenvatting

Meedoen aan dit onderzoek geschiedt volledig vrijwillig. Het staat u geheel vrij om wel of niet mee te doen. Samengevat betekent het dat als u deelneemt:

- u bereid bent mee te werken aan het onderzoek waarin metingen aan de schouders worden gedaan;
- u akkoord gaat met het gebruik van de verzamelde data ten behoeve van het onderzoek;
- u zich realiseert dat u geen onderzoeksuitslag voor uzelf kunt verwachten.

Namens de onderzoeker(s), bij voorbaat zeer hartelijk dank voor uw eventuele medewerking.

Jelle Broekzitter, MSc Student

Cognitive Robotics Laboratory

TU Delft

Proefpersoongegevensformulier

Participant nummer:
Persoonsinformatie
Deze informatie is vertrouwelijk en wordt niet beschikbaar gemaakt voor derden.

Leeftijd :

Voorkeurshand : Rechts / Links

Tijdsduur experiment :

Cognitive Robotics Laboratory

PARTICIPANT CONSENT FORM

Study Title	Workspace extension in grasp-by-wire		
Participant Name:		**Date:**	
Researcher Name:	Jelle Broekzitter		

This section to be completed by the participant:

Please tick the box at the end of each statement if you agree with it.

1. I confirm that I have read and understood the Information Sheet for the above study.
2. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.
3. I understand that my participation is voluntary and that I am free to withdraw from the study, without giving any reason.
4. I agree to the storage and use of personal information for the purposes of this study.
5. I agree to take part in the above study.

Signed:

Name in capitals:

Date:

This section to be completed by the researcher

I certify that this participant has read, properly completed and signed the screening and consent forms, witnessed by myself:

Signed:

Date:

Cognitive Robotics Laboratory

Please note: All data arising from this study will be held and used in accordance with the Data Protection Act. The results of the study will not be made available in a way that could reveal the identity of individuals.

Cognitive Robotics Laboratory

DEELNAME TOESTEMMINGSFORMULIER

Titel studie:	Workspace extension in grasp-by-wire		
Naam Deelnemer:		**Datum:**	
Naam Onderzoeker:	Jelle Broekzitter		

Door de deelnemer in te vullen:

Indien akkoord met de onderstaande stellingen, vink het bijstaande vakje aan.

1. Ik bevestig dat ik het informatie formulier, horend bij de bovenstaande studie, gelezen en begrepen heb.

2. Ik heb de mogelijk gehad de informatie goed in me op te nemen en vragen te stellen, die naar tevredenheid beantwoord zijn.

3. Ik begrijp dat mijn deelname volledig vrijwillig is en dat ik mij op elk moment kan terugtrekken, zonder het opgeven van een reden.

4. Ik sta toe dat mijn persoonlijke informatie wordt opgeslagen ten behoeve van deze studie.

5. Ik stem toe met deelname aan de bovenstaande studie.

Handtekening:

Naam in blokletters:

Datum:

Door de onderzoeker in te vullen:

Hierbij verklaar ik dat de deelnemer het toestemmingsformulier grondig heeft doorgelezen en vervolgens getekend, en ik daarvan zelf getuige was:

Handtekening:

Datum:

Belangrijk! Alle data voortkomend uit deze studie zal opgeslagen en behandeld worden volgens de Data Protection Act. De resultaten van deze studie zullen niet op enige manier openbaar gemaakt worden waarbij het mogelijk is deze direct aan de identiteit van de deelnemers te koppelen.

Delft University of Technology

INSPECTION REPORT FOR DEVICES TO BE USED IN CONNECTION WITH HUMAN SUBJECT RESEARCH

This report should be completed for every experimental device that is to be used in interaction with humans and that is not CE certified or used in a setting where the CE certification no longer applies[1]. The first part of the report has to be completed by the researcher and/or a responsible technician. Then, the safety officer (AMA – Arbo en milieu adviseur) of the corresponding faculty has to inspect the device and fill in the second part of this form. Please visit https://intranet.tudelft.nl/arbeidsomstandigheden/arbeidsomstandigheden/overzicht-amas/ for more information.

Note that in addition to this, all experiments that involve human subjects have to be approved by the Human Research Ethics Committee of TU Delft. You can find more information on the procedures at http://www.hrec.tudelft.nl/

Device identification (name, location): Prosthetic hand simulator, 3ME, Cognitive Robotics lab (34-F-0-220)

Configurations inspected[2]: master to virtual slave (unilateral control with haptic force feedback)

Type of experiment to be carried out on the device:[3] teleoperated one-dimensional precision/speed task

Name(s) of applicants(s): Henri Boessenkool

Job title(s) of applicants(s): Lab coordinator

Date: 6-12-2018

Signature(s): H. Boessenkool

Setup summary

---

1 Modified, altered, used for a purpose not reasonably foreseen in the CE certification

2 If the devices can be used in multiple configurations, otherwise insert NA

3 e.g. driving, flying, VR navigation, physical exercise, ...

The device is called the prosthetic hand simulator. It consists of one side of a one-dimensional, bilateral master-slave setup built in-house by Goran Christiansson. The position is measured by a LVDT, which is then used to calculate the desired feedback force from the compression of a virtual spring by the perfect virtual slave.

This force is delivered to the user by an electrical motor capable of providing constant torque pulling on a Bowden cable connected to the user's shoulders. The cable is anchored to the skin over the shoulders by two plastic connectors that are stuck on using (sport)tape. One tab anchors the outer cable, while the farthest tab anchors the inner cable that transfers the forces. The forces are limited to 18N because of hardware limitations. There is a 3.5N pretension exerted on the cable to return de device to the open position when the user relaxes.

The device is fitted with an emergency stop button, which, when engaged, stops the device and disables the motor amplifier.

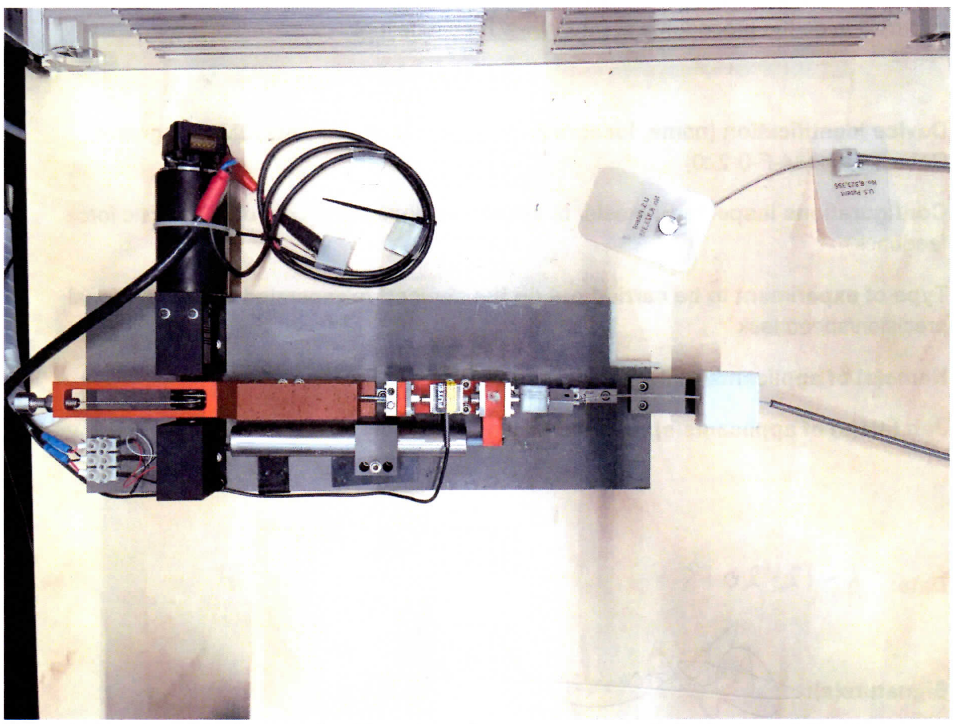

Figure 1: *Top view of the input device. The red metal parts move as one in the horizontal direction, exerting force on the bowden cable on the right. The plastic connection points at the end of the cable are anchored to the skin using tape.*

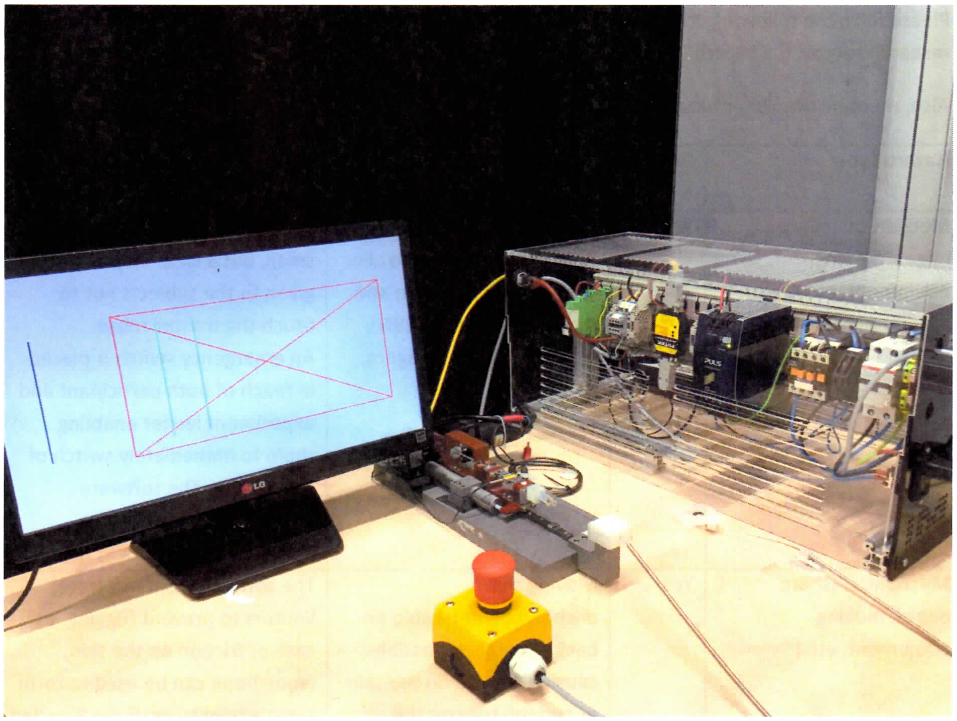

Figure 2: *Overview of the setup, showing the virtual environment on the screen.*

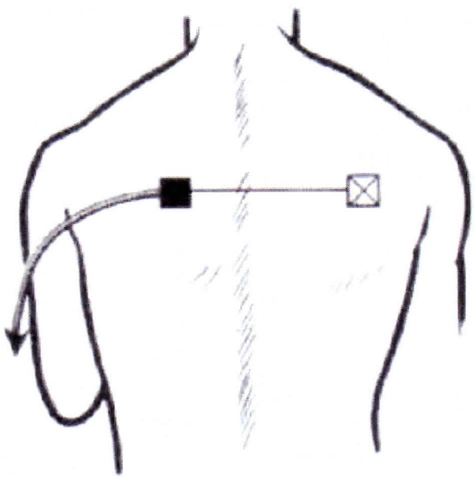

Figure 3: *Schematic view of the connection to the skin.*

Risk checklist

Please fill in the following checklist and consider these hazards that are typically present in many research setups. If a hazard is present, please describe how it is dealt with.

Also, mention any other hazards that are present.

Hazard type	Present	Hazard source	Mitigation measures
Mechanical (sharp edges, moving equipment, etc.)	Yes	Moving linkage bar and Bowden cable at controller (displacement of 4cm and motor forces up to 18N), possibly pinching fingers, hair or clothes.	The displacement and forces are small, but a clear instruction is given to the subjects not to touch the master robot. An emergency switch is placed in reach of both participant and experiment leader enabling them to immediately switch of the system. The software contains (rate) limiters to prevent tugging
Mechanical (sharp edges, moving equipment, etc.)	Yes	Moving skin anchor/bowden cable on back of subject. Possibly causing friction on the skin or sudden tugs on the shoulders. Loose end on the Bowden cable.	The software contains (rate) limiters to prevent tugging. In case of friction on the skin, (sport)tape can be used to form a protective layer. If the Bowden cable, after adjusting, has a loose end that exceeds the size of the plastic pads it will be covered with tape. An emergency switch is placed in reach of both participant and experiment leader enabling them to immediately switch of the system.
Electrical	Yes	Motor contacts on master and slave device (max. theoretical output according amplifier specs: +/- 40V, 10A peak).	The motor cable/contacts are insulated and the device is placed on a distance to prevent accidental touching. Clear instructions not to touch the device, attention of the experiment leader on the behaviour of the participant.
Electrical	Yes	The master device is connected to the controller which is connected to the power grid. In case of components	The master device and controller unit are all grounded and an earth leakage circuit breaker is installed. Fuses are installed to

		fail participant could be in contact with dangerous voltage.	prevent unsafe situations in case of a shortcut. The controller unit is protected by a plastic cover. The interface with the subject (Bowden cable + skin anchors) is electrically insulated from the controller.
Structural failure	Low	Possible failure of bearings or links.	Clear instructions and checking setup each time before measurements.
Touch Temperature	Low	Possible heating of motors	Clear instructions not to touch the equipment and actuators placed sufficiently far away to prevent accidental touching.
Electromagnetic radiation	Low	EMC from small motors	Clear instruction not to place wallet or phone next to motors.
Ionizing radiation	No		
(Near-)optical radiation (lasers, IR-, UV-, bright visible light sources)	No		
Noise exposure	No		
Materials (flammability, offgassing, etc.)	No		
Chemical processes	No		
Fall risk	No		
Other:			
Other:			
Other:			

Device inspection

(to be filled in by the AMA advisor of the corresponding faculty)

Name: P. Kohne

Faculty: 3ME/IO

The device and its surroundings described above have been inspected. During this inspection I could not detect any extraordinary risks.

(Briefly describe what components have been inspected and to what extent (i.e. visually, mechanical testing, measurements for electrical safety etc.)

Date: 6-12-2018

Signature:

Inspection valid until[4]:

Note: changes to the device or set-up, or use of the device for an experiment type that it was not inspected for require a renewed inspection

4 Indicate validity of the inspection, with a maximum of 3 years

Delft University of Technology
ETHICS REVIEW CHECKLIST FOR HUMAN RESEARCH
(Version 10.10.2017)

This checklist should be completed for every research study that involves human participants and should be submitted before potential participants are approached to take part in your research study.

In this checklist we will ask for additional information if need be. Please attach this as an Annex to the application.

Please upload the documents (go to this page for instructions).

Thank you and please check our website for guidelines, forms, best practices, meeting dates of the HREC, etc.

I. Basic Data

Project title:	**Workspace extension on grasp-by-wire with shoulder harness**
Name(s) of researcher(s):	**Jelle Broekzitter**
Research period (planning)	**Dec - March**
E-mail contact person	**jelle.broekzitter@gmail.com**
Faculty/Dept.	**3ME biomedical eng.**
Position researcher(s):[1]	**student**
Name of supervisor (if applicable):	**Dick Plettenburg, David Abbink, Henri Boessenkool**
Role of supervisor (if applicable):	**professor, professor, Ph.D**

[1] For example: student, PhD, post-doc

II. A) Summary Research

(Please very briefly (100-200 words) summarise your research, stating the question for the research, who will participate, the number of participants to be tested and the methods/devices to be used. Please avoid jargon and abbreviations).

The goal of my research is to find a promising method to apply workspace extension to a by-wire application of a grasping prosthesis controlled by a shoulder harness. The device consists of a one-dimensional master-slave setup in which the slave is entirely virtual.

The participant will grasp a squishy object in a virtual, one-dimensional environment and will be performing a precision-speed task to compress the object to a given target. The participant will be provided with both visual feedback and haptic force feedback. The experiment is supposed to give more insight in the strengths and limits of the control behaviour of the shoulders with a harness at these force levels.

The master device is connected to the shoulders using two plastic tabs and double-sided- or sport tape. These tabs anchor the outer- and inner cable to the skin and form the shoulder harness. The tabs will be disinfected using rubbing alcohol before being applied. performing a shrugging motion increases the distance between the tabs, displacing the cable. An algorithm then calculates the required feedback force to be exerted on the cable by the electric motor.

To achieve sufficient statistical power, I aim to test 20-30 participants.

B) Risk assessment

(Please indicate if you expect any potential risks for the participants as a result of your research and, if so, how you will try to minimize these).

The participant is required to perform around 75 trials (including 15 practise trials) of the task, which should take between 15-30 minutes. The cable forces that the participant experiences on the shoulders are 18N at most; the recommended upper force limit is 40N [D.H. Plettenburg et al., 2011], so the experiment stays well within this limit. The 'shrug' movement is an unnatural movement for grasp control, which could cause some mild discomfort. This should be mitigated by the low forces the user experiences, and the participant can ask for a break after every trial. Also, to prevent jerking on the shoulders, (rate) limiters are present in the software.

The connectors will be applied to the skin over the shoulders using double-sided or sport tape. In order to achieve this, the participant is required to remove all clothing that covers the torso. Tank Tops and bras that leave these areas bare are not allowed since they could cause friction forces on the inner cable, influencing the data. This could leave participants feeling uncomfortable. To mitigate these problems, the participants are informed about this before they agree to participate, the experiment will take place behind a curtain as to provide privacy during the experiment and - since the student conducting the experiment is male - only male participants will be admitted.

The system contains high- and low voltage circuits and some moving parts, which could cause injury to the participant. These dangers are mitigated by protective measures as explained in the approved device report.

The participants will sign an informed consent and can opt out of the experiment at any time without the obligation to provide a reason or explanation. No personal data will be stored except for age; all measured data will be saved anonymously. The participants will be asked to rate their experiences.

III. Checklist

Question	Yes	No
1. Does the study involve participants who are particularly vulnerable or unable to give informed consent? (e.g., children, people with learning difficulties, patients, people receiving counselling, people living in care or nursing homes, people recruited through self-help groups).		x
2. Are the participants, outside the context of the research, in a dependent or subordinate position to the investigator (such as own children or own students)?[2]		x
3. Will it be necessary for participants to take part in the study without their knowledge and consent at the time? (e.g., covert observation of people in non-public places).		x
4. Will the study involve actively deceiving the participants? (e.g., will participants be deliberately falsely informed, will information be withheld from them or will they be misled in such a way that they are likely to object or show unease when debriefed about the study).		x
5. Will the study involve discussion or collection of information on sensitive topics? (e.g., sexual activity, drug use, mental health).		x
6. Will drugs, placebos, or other substances (e.g., drinks, foods, food or drink constituents, dietary supplements) be administered to the study participants?		x
7. Will blood or tissue samples be obtained from participants?		x
8. Is pain or more than mild discomfort likely to result from the study?		x
9. Does the study risk causing psychological stress or anxiety or other harm or negative consequences beyond that normally encountered by the participants in their life outside research?		x
10. Will financial inducement (other than reasonable expenses and compensation for time) be offered to participants?		x
Important: you answered 'yes' to any of the questions mentioned above, please submit a full application to HREC (see: website for forms or examples).		

[2] **Important note concerning questions 1 and 2.** Some intended studies involve research subjects who are particularly vulnerable or unable to give informed consent .Research involving participants who are in a dependent or unequal relationship with the researcher or research supervisor (e.g., the researcher's or research supervisor's students or staff) may also be regarded as a vulnerable group . If your study involves such participants, it is essential that you safeguard against possible adverse consequences of this situation (e.g., allowing a student's failure to complete their participation to your satisfaction to affect your evaluation of their coursework). This can be achieved by ensuring that participants remain anonymous to the individuals concerned (e.g., you do not seek names of students taking part in your study). If such safeguards are in place, or the research does not involve other potentially vulnerable groups or individuals unable to give informed consent, it is appropriate to check the NO box for questions 1 and 2. Please describe corresponding safeguards in the summary field.

11. Will the experiment collect and store videos, pictures, or other identifiable data of human subjects? [3] If "yes", please fill in Annex 1 and make you sure you follow all requirements of the applicable data protection legislation. In addition, please provide proof by sending us a copy of the informed consent form.		x
12. Will the experiment involve the use of devices that are not 'CE' certified? *Only, if 'yes': continue with the following questions:*	x	
➢ Was the device built in-house?	x	
➢ Was it inspected by a safety expert at TU Delft? (*Please provide device report, see: HREC website*)	x	
➢ If it was not built in house and not CE-certified, was it inspected by some other, qualified authority in safety and approved? *(Please provide records of the inspection).*		
13. Has or will this research be submitted to a research ethics committee other than this one? (*if so, please provide details and a copy of the approval or submission).*		x

IV. Enclosures (tick if applicable)

- ○ Full proposal (if 'yes' to any of the questions 1 until 10)
- ○ Informed consent form (if 'yes' to question 11)
- ● Device report (if 'yes' to question 12)
- ○ Approval other HREC-committee (if 'yes' to question 13)
- ○ Any other information which might be relevant for decision making by HREC

V. Signature(s)

Signature(s) of researcher(s)
Date: 06-12-2018

Signature research supervisor (if applicable)
Date: 06-12-2018

---

[3] Note: you have to ensure that collected data is safeguarded physically and will not be accessible to anyone outside the study. Furthermore, the data has to be de-identified if possible and has to be destroyed after a scientifically appropriate period of time. Also ask explicitly for consent if anonymised data will be published as open data.

Date 21-12-2018
Contact person Ir. J.B.J. Groot Kormelink, secretary HREC
Telephone +31 152783260
E-mail j.b.j.grootkormelink@tudelft.nl

Human Research Ethics Committee
TU Delft
(http://hrec.tudelft.nl/)

Visiting address
Jaffalaan 5 (building 31)
2628 BX Delft

Postal address
P.O. Box 5015 2600 GA Delft
The Netherlands

Ethics Approval Application: Workspace extension on grasp-by-wire with shoulder harness
Applicant: Boessenkool, Henri

Dear Henri Boessenkool,

It is a pleasure to inform you that your application mentioned above has been approved.

Good luck with your research!

Sincerely,

Prof. Dr. Sabine Roeser
Chair Human Research Ethics Committee TU Delft

Prof.dr. Sabine Roeser
TU Delft
Head of the Ethics and Philosophy of Technology Section
Department of Values, Technology, and Innovation
Faculty of Technology, Policy and Management
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www.tbm.tudelft.nl/sroeser

Date: June 21, 2018
Version 1.6

Wiring Description

Finger Pertubator

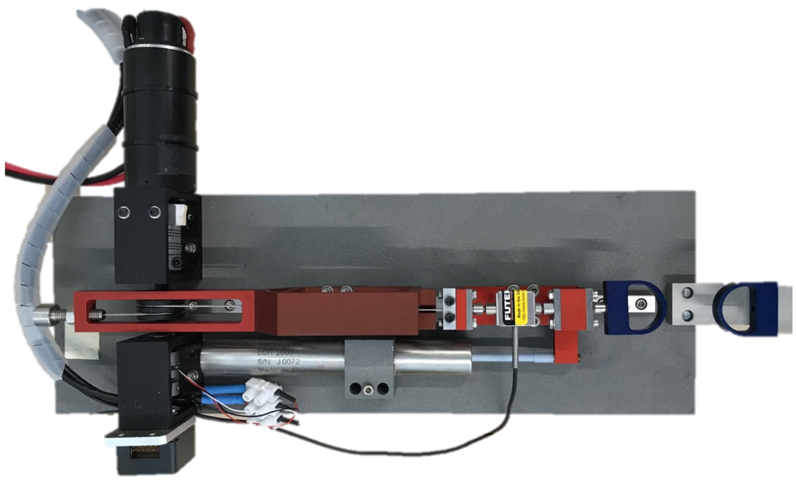


Figure 1 - *Top view of the mechanical system*

Table of Contents

1 Setup Overview

1.1 Mechanical system

The Haptic Gripper designed by Göran A. V. Christiansson consisted of both a master and a slave device. The current setup of the finger pertubator exists only out of one module. The differences between the original setup and the current setup are marked by the red crosses below. In the current setup the encoder is not in use, and the adjustable damper and adjustable stiffness have both been removed.

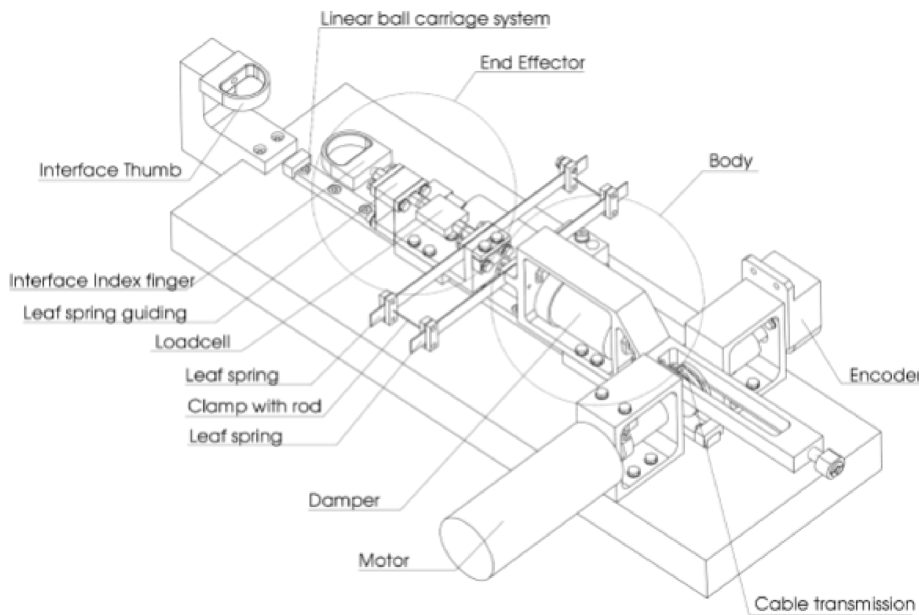
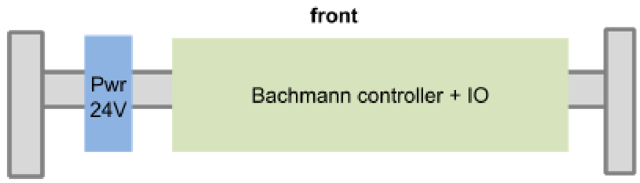


***Figure** 2: Overview mechanical system*

1.2

Controller system



<table>
<tr><th colspan="4">Bachmann overview</th></tr>
<tr><td colspan="4">
</td></tr>
<tr><td>NT255
Slot 1</td><td>AIO216
Slot 2-3</td><td>AIO288
Slot 4</td><td>DIO232
Slot 5</td></tr>
</table>

Figure 3*: Overview of the electrical system and RealTime Bachmann controller, front view*

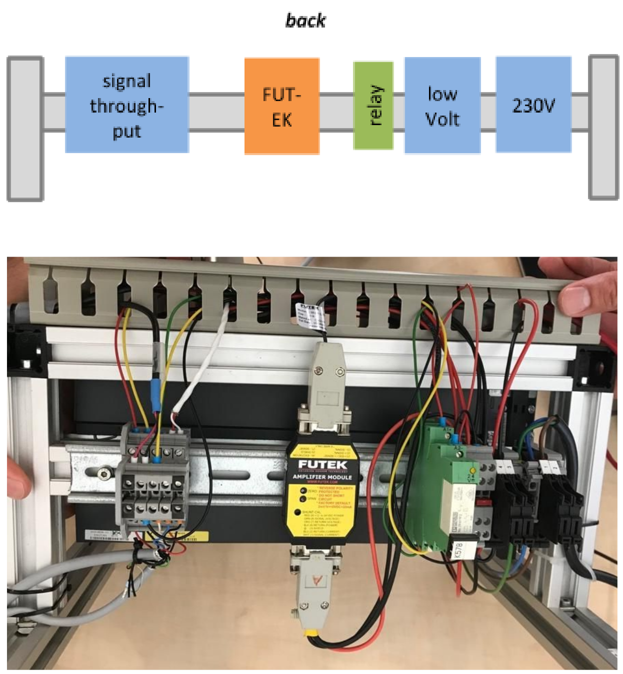


***Figure** 4**:** Overview of the electrical system, back view*

1.3 Aerotech Amplifier

Linear motor amplifier: Aerotech BL-10-40-B. Three channels, 5A continuous, 10A max (see spec. sheet).

***Figure** 5: Top view amplifier*

2 Wiring 230V / Low voltage circuit

The electric wiring of the 230V and the low voltage circuit are shown in Figure 6 and Figure 7

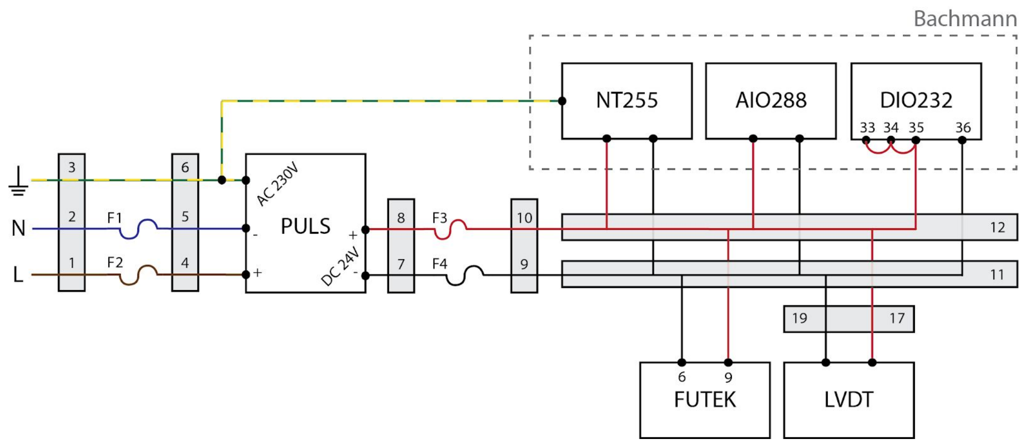


***Figure** 6: Electric wiring scheme 230v / Low voltage circuit*

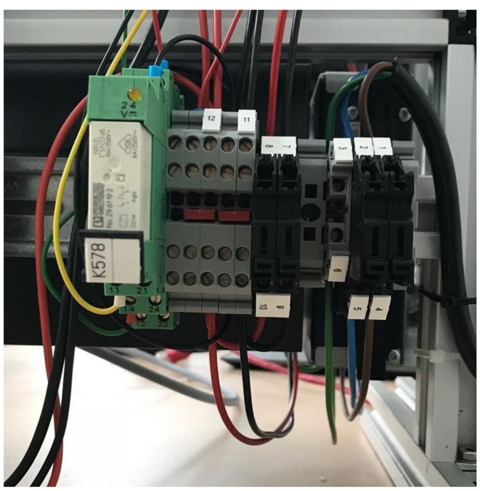


***Figure** 7: Picture of electric wiring 230V / Low voltage circuit*

Component list (see specification sheets for more details):

- PULS - Puls Dimension QS5.241 Power Supply, 24V, 5A.
- NT255 Bachmann module – Power Supply Module
- AIO288 Bachmann module – Analog input/output module (see also section: 3.6.1)
- DIO232 Bachmann module – Digital input/output module (see also section: 3.6.2)
- FUTEK L2357 + JM-2A – Force sensor + amplifier module, max. 45N (see also section: 3.3)
- LVDT, Schaevitz 2000 LCIT – Position sensor, max 50,8mm (see also section: 3.4)

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3 Wiring of signals

3.1 Emergency button/amplifier enable

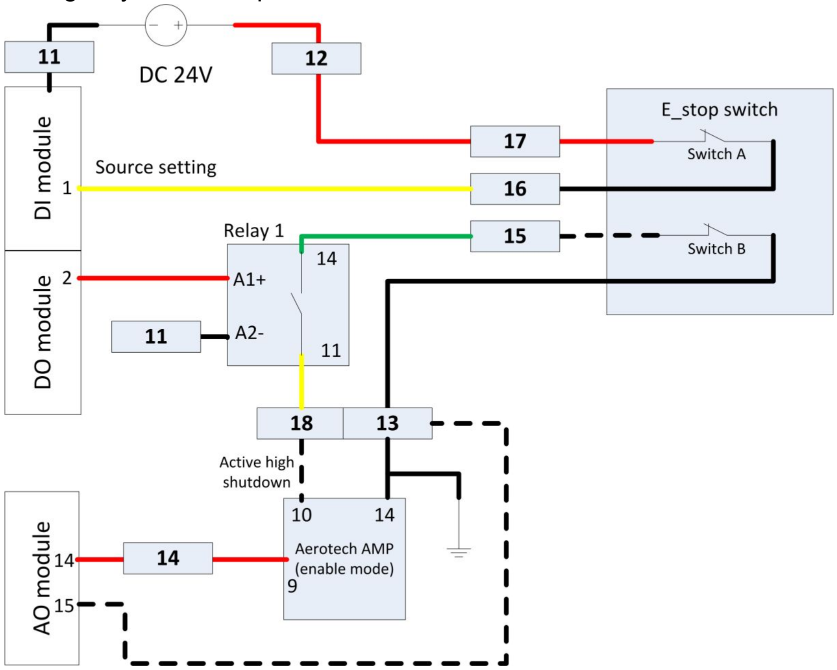

***Figure** 8: Electric scheme emergency button and amplifier enable*

3.2 Wiring of Motor Controller (Aerotech Amplifier)

The amplifier settings:
The amplifier is set to 'current mode' and 'multiple brush motors', see also "Aerotech BL hardwaremanual" section "3.3 *Torque Command Configuration (Current)"* and section *"3.7 Multiple Brush Motor"*.

Setting of DIP switches: closed:1-8 (Current limits) ,10 (Mode) // open: 9 (Test).

3.2.1 Amplifier enable

The amplifier is set to 'Active high shutdown' (Control Board Jumper Selection - JP6: Active High Shutdown, see Aerotech BL hardwaremanual, p47), meaning that the amplifier is only enabled if the 'shutdown input' (J101-10) is connected with the ground (J101-14). The enable circuit contains a relay-switch (Normally Open) and an Emergency switch.

The amplifier will only be enabled if the EM-switch is not pressed and the relay is digitally activated from the Bachmann controller. The implementation is fail save; disconnected cables or power drop will result in a disabled amplifier.

***Table** 1: Wire connections for amplifier enable, see also* Figure 8*)*

Signal	Enable	Signal ground*	Ground	Shield
J101 connector (Aerotech BL)	10	7	14	1
Cable	WH	BK	BK	Shield
Feedthroug h #	18		13	
Cable	YL		BK	
EM switch			Switch2	
Cable			WH	
Feedthroug h #			15	
Cable			GN	
Relay 1	11		14	

*Signal ground didn't work. Ground (pin 14 = shield) appeared to work.

3.2.2 Analog input control signals

The commanded motor current is send from an Bachmann analog out channel to the Aerotech amplifier. For this setup only channel A of the motor controller is used.

***Table** 2: Wire connections for amplifier input signals, see also* Figure 8*):*

Signal	Control Sign A	Control Sign B	Control Sign C	Signal ground*	Ground	Shield
J101 connector (Aerotech BL)	9	22	12	7	14	1
Cable	RD	BL	GN	BK	BK	Shield
Feedthroug h #	14				13	
Cable	RD				WH	

Bachmann AIO288	14				15	

*Signal ground didn't work. Ground (pin 14 = shield) appeared to work.

3.2.3 Analog output to motor

The + wire (RD) of the motor is connected to TB101-A and the – wire (BK) of the motor to TB101-RT.

Used motor:

- Maxon motor A: RE35_90W, 118777 -> V: 30V, starting current: 24.4A (stall torque: 949mNm), **max. cont. current: 2,74A** (max.con.Torque: 107mNm).
- Maxon motor B: RE40_150W, 148867 -> V: 24V, starting current: 80.2A (stall torque: 2420mNm), **max. cont. current: 6A** (max.con.Torque: 177mNm).

3.2.4 Connector pin assignment Aerotech BL Amplifier

Connector J101 (25-pin "D" type, female) provides the interface for input and output control connections.

Table 2-8: Connector J101 Pin Assignment

Pin	Signal	Function	I/O
1	SHIELD	Chassis frame ground	Input
2	POWER	+5V Power for Encoder (250 mA max)	Output
3	TACH+	Tachometer input for velocity feedback (encoder vs. tach velocity feedback is jumper selectable).	Input
4	HA	Hall-Effect Sensor A (brushless motors only)	Input[1]
5	COS	Encoder Cosine +	Input
6	COS-N	Encoder Cosine -	Input
7	GROUND	Signal common. Electrical reference for all control circuitry on amplifier.	Input
8	+INPUT	Non-inverting input of differential input circuit.	Input
9	ICMDA	Current Command A	Input
10	SHUTDOWN	Shut off power stage (and remove all power to the motor).	Input[1]
11	+ILMT	CW directional current limit input.	Input[1]
12	ICMDC	Current Command C	Input
13	–	–	–
14	GROUND	Signal common of an encoder	N/A
15	TACH-	Recommended reference input for tachometer. This point is identical to signal common.	Input
16	HB	Hall-Effect Sensor B (brushless motors only)	Input[1]
17	HC	Hall-Effect Sensor C (brushless motors only)	Input[1]
18	SIN	Encoder Sine +	Input
19	SIN-N	Encoder Sine -	Input
20	Power	+5V Power for Encoder (250 mA max)	Output
21	-INPUT	Inverting input of differential input circuit.	Input
22	ICMDB	Current Command B	Input
23	FAULT	Indicates the status of the power stage (amplifier enabled or faulted).	Output
24	-ILMT	CCW directional current limit input.	Input[1]
25	-ICMD	Current command monitor. Representative of the current command (self commutating modes only).	Output

1. Denotes input pull up to internal +5 VDC through a 10K resistor

Location:

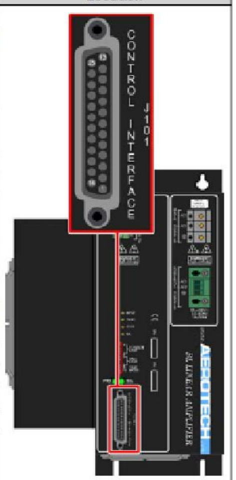

***Figure** 9: Connector J101 pin assignment, Aerotech BL hardware manual, p. 15.*

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3.3 FUTEK Load cell amplifier (Force Measurements)

Details:

- Futek amplifier: CSG110 (JM-2A)
- Futek loadcell: LBS200(L2357) -> FSH00104 (range: 44.5 N, M3x0.5 // 2mv/V)

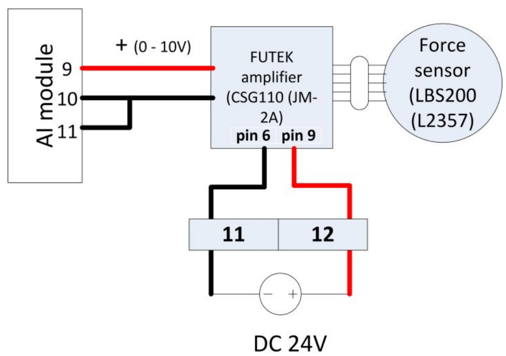


Figure 10***:*** *Connections Futek load cell amplifier*

3.4

LVDT Linear distance sensor

Details:

- 2000LCIT (Schaevitz Sensors) -> Range +/-25mm, Input V: 7-36V, output V: 0.5-4.5V, 0.018V/mm

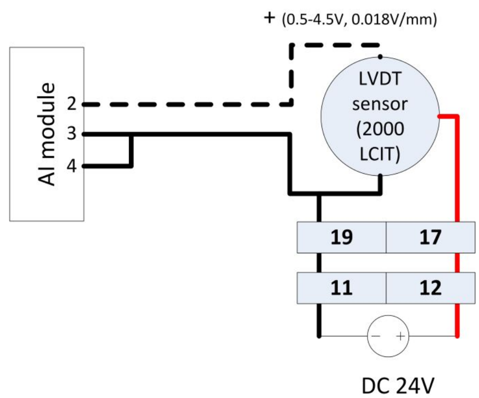


***Figure** 11: Connections LVDT*

3.5 Cable feedthrough

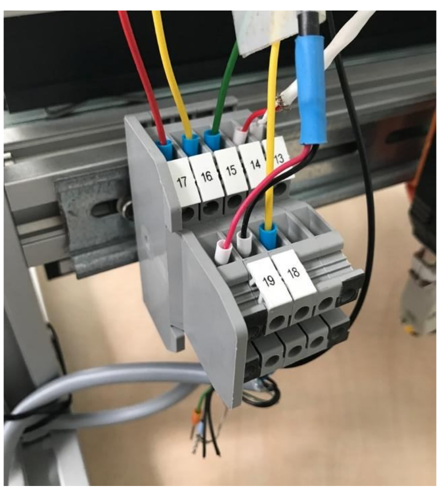


***Figure** 12: Picture of cable feedthrough signals*

3.6 Wiring of Bachmann

See also specification sheets.

3.6.1 AIO288

Slot 5		**AIO288**	
Chan.	*Pin No.*	*Settings*	*Description*
1	1,2,3	IN: +/- 10V	LVDT A
2	20,21,22	IN: +/- 10V	LVDT B
3		IN: +/- 10V	spare
4		IN: +/- 10V	spare
5	8,9,10	IN: +/- 10V	Force sensor A
6	27,28,29	IN: +/- 10V	Force sensor B
7		IN: +/- 10V	spare
8		IN: +/- 10V	spare
9	14,15,16	OUT: +/- 10V	Motor A
10	17,18,19	OUT: +/- 10V	Motor B
11		OUT: +/- 10V	spare
12		OUT: +/- 10V	spare
13		OUT: +/- 10V	spare
14		OUT: +/- 10V	spare
15		OUT: +/- 10V	spare
16		OUT: +/- 10V	spare

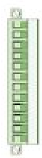
	Connector 1/2/3/4 Pin				Signal	Description	Channel			
	1	20	39	58	⏚	Shield (functional ground)				
	2	21	40	59	U+	Positive input ±10 V, ±1 V				
	3	22	41	60	U/I-	Negative input ±10 V, ±1 V; I				
	4	23	42	61	0V Ref	Reference connection for ±10 V, ±1 V	1	2	3	4
	5	24	43	62	I+	Positive current input for 0 to 20 mA				
	6	25	44	63	+10 V	Potentiometer power supply +10 V				
	7	26	45	64	-10V	Potentiometer power supply -10 V				
	8	27	46	65	⏚	Shield (functional ground)				
	9	28	47	66	U+	Positive input for ±10 V, ±1 V; Pt100, Pt1000				
	10	29	48	67	U/I-	Negative input for ±10 V, ±1 V; I; Pt100, Pt1000				
	11	30	49	68	0V Ref, PT +	Reference connection for ±10 V, ±1 V; Pt+	5	6	7	8
	12	31	50	69	I+	Positive current input for 0 to 20 mA				
	13	32	51	70	PT-	Drain for Pt100, Pt1000				
	14	33	52	71	U+	Positive output ±10 V				
	15	34	53	72	0V Ref	Reference connection for ±10 V	9	10	11	12
	16	35	54	73	⏚	Shield (functional ground)				
	17	36	55	74	U+	Positive output ±10 V				
	18	37	56	75	0V Ref	Reference connection for ±10 V	13	14	15	16
	19	38	57	76	⏚	Shield (functional ground)				

Tab. 509: Pin assignment Connectors 1/2/3/4

3.6.2 DIO232

Slot 6	**DIO232**	
Chan.	*Settings*	*Description*
1	DI	E-stop button
2	DO	Amplifier Enable
..32		

Digital Inputs / Outputs

	Connector 1		Connector 2		Connector 3	
	Pin	Signal	Pin	Signal	Pin	Signal
	1	DIO1	13	DIO13	25	DI9
	2	DIO2	14	DIO14	26	DI10
	3	DIO3	15	DIO15	27	DI11
	4	DIO4	16	DIO16	28	DI12
	5	DIO5	17	DI1	29	DI13
	6	DIO6	18	DI2	30	DI14
	7	DIO7	19	DI3	31	DI15
	8	DIO8	20	DI4	32	DI16
	9	DIO9	21	DI5	33	U1
	10	DIO10	22	DI6	34	U2
	11	DIO11	23	DI7	35	+ (U_Logic)
	12	DIO12	24	DI8	36	(GND)

Tab. 151: Pin assignment digital inputs/outputs [illegible]