Validation of a Limited Information Shared Controller: A Comparative Study

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***Abstract*—This paper presents the validation and the comparative study of a shared control concept for a large vehicle manipulator (LVM). The state-of-the-art controlling a LVM is manual control: The operator controls the manipulator to carry out a specific task and keeps the vehicle on the road. Easing the work for the operator, an automatic lane-keeping of the vehicle can be taken into account: An automation of the vehicle which keeps it on its reference, but without taking into consideration of the manipulator's specific task. However, the operator has his specific task with the manipulator, and therefore, such automation may not be satisfying. Therefore, this paper presents the validation and compares the Limited Information Shared Controller (LISC) proposed previously with the manual control mode. This step is crucial, showing the concept's applicability and benefits compared to the state-of-the-art solution. Thus, the LISC is compared with a non-cooperative controller (NCC) and the manual mode on a real-time simulator with test subjects. It has a more realistic experimental setup than in other studies because there is no predefined manipulator reference. The study results indicate that the NCC can lead to undesired motions of the overall system because the test subjects cannot carry out their specific task. On the other hand, the proposed the LISC of the vehicle can reduce the working load while supporting the operator in carrying out the manipulator's specific task.**

***Index Terms*—Large Vehicle Manipulator, Mobile Manipulator, Human-Machine Cooperation, Limited Information Shared Controller, Validation, Simulator Experiment**

I. Introduction

Large Vehicle Manipulators (LVM) are used in diverse applications like farming [1], forestry [2] or road maintenance [3]. Such systems are usually controlled by a human operator, as the working environment is unstructured. Fig. 1 shows a LVM, with two manipulators attached to the vehicle. The operator has to carry out a specific task with the manipulator and has to keep the vehicle on the road or on its reference path. These tasks (controlling the manipulator and driving the vehicle) are mentally (and sometime physically) demanding for the human. Full automation of a LVM is not possible due to safety regulations (e.g. for road maintenance a human still has to monitor the system) and due to the challenging working environment of the manipulator, [3], [4].

The convention solution to reduce the operator's workload without automation - especially for machines with multiple manipulators - is to divide the tasks between two workers: one person who is responsible for driving the vehicle and another who is only in charge of controlling the manipulators. In this case, the tasks can be performed cooperatively, where the communication between the two people is mainly verbal or visual. The person operating the vehicle tells the person driving how fast and how far away from the edge of the road the vehicle should be. This cooperation is central to the quality of the work product. The use of two workers on one vehicle is associated with a high cost impact. Therefore, the work should be performed with only one person, which can be very demanding.

A goal is to reproduce this cooperation with an advanced automation helping the operator on a LVM to carry out the specific task. This means that the controller of the vehicle adjusts and supports this task accordingly, similar to two workers operating the LVM. However, the controller has no information about the task specific of the human. To overcome this challenge, [5] proposes the *Limited Information Shared Controller* (LISC), which can support the operator without information about the manipulator's state and goals.

This paper presents the validation of the design concept of the LISC [6] and a comparison with the actual state-of-the-art control, which is the manual control mode without automation. In this case, the operator has to control the manipulator and keeps the vehicle on its reference simultaneously. The experimental setup in this work is more realistic compared to earlier studies, since no trajectory of the manipulator is given to the test subjects in advance. They had to determine the trajectories from one goal to the next online themselves.

In the following, Section II presents the state-of-the-art and in Section III, the concept of the LISC is briefly introduced.

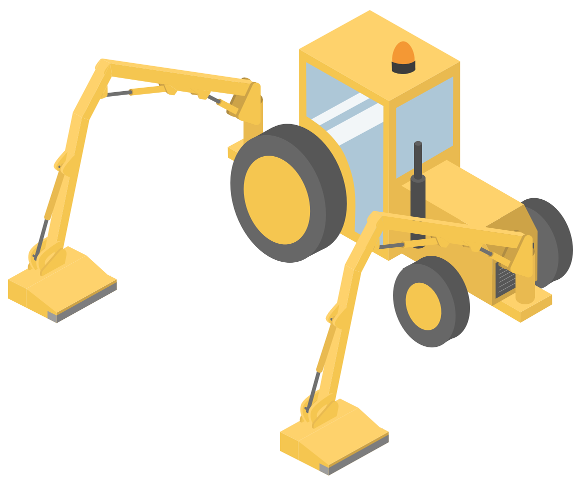

Fig. 1: An example of a large vehicle-manipulator: Two hydraulic actuated manipulators are attached to a tractor.

The test-bench and the simulator experiment are introduced in Section IV. Section V discusses the results of the experiment before the paper's conclusion is provided in Section VI.

II. State-of-the-Art

First, this section presents the related works for the control of large manipulators, robotic manipulators and field robots from the literature. Then a short overview of the state-of-the-art in the field of human machine interaction is provided.

A. The Control of Large Manipulators and Field Robots

The full automation of a hydraulic manipulator with a fixed base is investigated in the literature, see e.g. [7], [8] or [9]. In these works, detailed and simplified models are developed to control the position and the velocity of the end-effector. However, they assume that the environment and the system are fully perceivable with the sensors installed on hydraulic manipulator. Apart from [10], no cooperation between the human and the automation has been taken into account for the control of the hydraulic actuated large manipulators. In [10], a simple linear velocity combination shared controller is proposed, which was able to ease the workload of novice operators.

For the control and navigation problem in the field robots (e.g. guide a tractor on a rural roads [11]), there are robust solutions, which can handle these challenging situations for off-road wheeled robots. Modelling and controlling wheeled robots without a robotic arm are discussed e.g. in [12].

However, non of the works from the state-of-the-art provides a model-based design of shared controllers for hydraulic manipulators. Furthermore, the works either focus on the control of the vehicle in challenging situations or on the automation of the manipulator, but none of them treats these two subsystems jointly.

B. Human-Machine Interaction

The topic of human-machine cooperation is in the focus of several academic research works. There exist general frameworks [13]–[15] and various applications: e.g. in automotive [16], semi-auto pilots of planes [17], wheel chairs [18]. These works assume a common control interface, which is controlled by the automation and the human jointly.

In [19] and [20], design methods are presented, which compute systematically the control law of a shared controller. The methods are based on the theory of differential games and are used as the starting point for the LISC design. Another difference in this paper is that the shared control happens with two input devices: A joystick and a steering wheel. In addition, this paper does not include haptic interaction via a common input device that is controlled jointly by humans and automation.

III. Design of a Limited Information Shared Controller

This section provides a brief overview of the LISC concept, which is introduced in [5].

A. Concept of the Limited Information Shared Controller

In robotic applications, it is a general approach to describe and model dynamic systems in the so-called Frénet Frame see [12, Chapter 49.2.3]. Therefore, the system of the LISC is modelled relative to its references and the variation of the references is described as an additional disturbance for the system, see (1). Furthermore, it is assumed that the dynamic system can be split in a automation-controlled ($\boldsymbol{x}_\mathrm{m}$, measurable for the automation) and a human-controlled part ($\boldsymbol{x}_\mathrm{um}$, unmeasurable for the automation) for the LISC. Furthermore, the human-controlled, unmeasurable states $\boldsymbol{x}_\mathrm{um}$ have no influence on the automation-controlled states $\boldsymbol{x}_\mathrm{m}$[1]. The resulting system equations are

$$\begin{aligned}\dot{\boldsymbol{x}}_\mathrm{m}(t) =& \mathbf{A}_\mathrm{m}\boldsymbol{x}_\mathrm{m}(t) + \mathbf{B}^{(a)}\boldsymbol{u}^{(a)}(t) + \dot{\boldsymbol{r}}_\mathrm{m}(t), && \text{(1a)}\\ \dot{\boldsymbol{x}}_\mathrm{um}(t) =& \mathbf{A}_\mathrm{um}\boldsymbol{x}_\mathrm{um}(t) + \mathbf{A}_\text{um-m}\boldsymbol{x}_\mathrm{m}(t)\\ &+\mathbf{B}^{(\mathrm{h})}\boldsymbol{u}^{(\mathrm{h})}(t) + \dot{\boldsymbol{r}}_\mathrm{um}(t), && \text{(1b)}\\ \boldsymbol{y}(t) =& \mathbf{I}\cdot\boldsymbol{x}_\mathrm{m}(t), && \text{(1c)}\end{aligned}$$

where $\dot{\boldsymbol{r}}_\mathrm{m}$ and $\dot{\boldsymbol{r}}_\mathrm{um}$ are the changes of the measurable and unmeasurable reference trajectories, respectively and $\mathbf{I}$ is the identity matrix.

The introduction of the so called *cooperation state* is the main idea of the LISC [5]. This cooperation state encapsulates the interaction of automation and human. A general definition from [5] is:

Definition 1 (Cooperation State): In a cooperative setup, we call the function

$$\boldsymbol{x}_\kappa(t) = \boldsymbol{\xi}\left(\boldsymbol{u}^{(\mathrm{a})}(t,\boldsymbol{x}), \boldsymbol{u}^{(\mathrm{h})}(t,\boldsymbol{x})\right), \tag{2}$$

the cooperation state, which can characterize the result of the interaction between automation and human.

The cooperation state (2) enables a modelling of the interaction between human and machine in the Frénet Frame with error coordinates: If $\boldsymbol{x}_\kappa = \mathbf{0}$ holds, the two players are currently in an equilibrium, such that non of the agents would change his/her actual control strategy. For linear time-invariant systems, the cooperation state is chosen to

$$\boldsymbol{x}_\kappa(t) = \boldsymbol{\Xi}^{(\mathrm{a})}\boldsymbol{u}^{(\mathrm{a})}(t) + \boldsymbol{\Xi}^{(\mathrm{h})}\boldsymbol{u}^{(\mathrm{h})}(t), \tag{3}$$

where the matrices $\boldsymbol{\Xi}^{(\mathrm{a})}$ and $\boldsymbol{\Xi}^{(\mathrm{h})}$ are parameters, which can characterize the cooperative setup. In [6], a method for a systematic identification of $\boldsymbol{\Xi}^{(\mathrm{a})}$ and $\boldsymbol{\Xi}^{(\mathrm{h})}$ is presented. This cooperation state (3) is used to extend (1), which leads to an extended model, in which all the system states are measurable:

$$\begin{bmatrix}\dot{\boldsymbol{x}}_m\\ \dot{\boldsymbol{u}}^{(\mathrm{a})}\\ \dot{\boldsymbol{x}}_\kappa\end{bmatrix} = \begin{bmatrix}\mathbf{A}_m & \mathbf{B}^{(\mathrm{a})} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{0}\end{bmatrix}\begin{bmatrix}\boldsymbol{x}_m\\ \boldsymbol{u}^{(\mathrm{a})}\\ \boldsymbol{x}_\kappa\end{bmatrix} + \begin{bmatrix}\mathbf{0}\\ \mathbf{1}\\ \boldsymbol{\Xi}^{(\mathrm{a})}\end{bmatrix}\dot{\boldsymbol{u}}^{(\mathrm{a})} + \begin{bmatrix}\mathbf{0}\\ \mathbf{0}\\ \boldsymbol{\Xi}^{(\mathrm{h})}\end{bmatrix}\dot{\boldsymbol{u}}^{(\mathrm{h})}. \tag{4}$$

Human inputs are implicitly considered by the bottom row of (4). The extended system state is $\boldsymbol{x}_\mathrm{e} = [\boldsymbol{x}_\mathrm{m}\ \boldsymbol{u}^{(\mathrm{a})}\ \boldsymbol{x}_\kappa]^T$, which is required to describe the dynamics of the cooperation state. Using (4), no explicit model of the human is necessary, which is the case by state-of-the-art approaches. Additionally,

[1] An exemplifying explanation is that if the (automated) vehicle moves, it impacts the manipulator position. On the other hand, the movement of the (human-controlled) manipulator does not influence the vehicle's motion.

the controller design is based on by the optimization of the single cost function

$$J_{\text{LISC}}^{(\text{a})} = \int_0^{t_{\text{end}}} \boldsymbol{x}_e^T \mathbf{Q}_{\text{LISC}}^{(\text{a})} \boldsymbol{x}_e + \dot{\boldsymbol{u}}^{(\text{a})^T} \mathbf{R}_{\text{LISC}}^{(\text{a})} \dot{\boldsymbol{u}}^{(\text{a})} \, \text{d}t. \tag{5}$$

Any conflict between automation and human occurring during the shared control can be handled and altered by adjusting the parameters of the cost function of (5). The optimum is computed as an standard linear quadratic control problem. The solution provides a feedback control law such as

$$\dot{\boldsymbol{u}}_{\text{LISC}}^{(\text{a})}(t) = -\mathbf{K}_{\text{LISC}}^{(\text{a})} \cdot \boldsymbol{x}_{\text{e}}(t), \tag{6}$$

from which the original system input is computed by

$$\boldsymbol{u}_{\text{LISC}}^{(\text{a})}(t) = \int_0^t \dot{\boldsymbol{u}}_{\text{LISC}}^{(\text{a})}(\tau) \, \text{d}(\tau). \tag{7}$$

Please note, that the input of the automation $\left(\boldsymbol{u}^{(\text{a})}\right)$ is considered as a system state in $\boldsymbol{x}_e$, which is only necessary for the controller design. Without loss of generality, it can be assumed that $\boldsymbol{u}^{(\text{a})}(t_0) = \mathbf{0}$. Finally, (7) allows the original system input $\boldsymbol{u}^{(\text{a})}(t)$ to be applied to the system.

B. Modelling of the Large Vehicle Manipulator

Fig. 2 shows the control model of the LVM [21], where both the vehicle and the manipulator are given in the frames P_{rv} and P_{rm} relative to their references $(\Gamma_{\text{rv}}, \Gamma_{\text{rm}})$. The system can be fully described by means of the lateral and orientation error of the vehicle (d_{v} and $\Delta\theta_{\text{v}} = \theta_{\text{v}} - \theta_{\text{r}}$), the lateral error of the manipulator (d_{m}) and the orientation error of the manipulator ($\Delta\alpha = \alpha - \alpha_{\text{r}}$) with α_{r} being the reference angle of the robotic arm. The system states are

$$\boldsymbol{x} = [d_{\text{m}}, \, \Delta\alpha, \, d_{\text{v}}, \, \Delta\theta_{\text{v}}] \, . \tag{8}$$

The vehicle can be controlled by means of speed v_{v} and steering $\boldsymbol{u}_1 = \delta$. The pose of the manipulator is set by the rate of its angle α and length a, $\boldsymbol{u}_2 = [\dot{\alpha}, \, \dot{\text{a}}]$. The variation of the references is described as an additional disturbance for the system, meaning $\boldsymbol{\kappa} = [\kappa_{\text{rv}}, \kappa_{\text{rm}}]$. A reasonable assumption is that the vehicle speed is constant, which leads to a LTI dynamic system

$$\dot{\boldsymbol{x}} = \mathbf{A} \cdot \boldsymbol{x} + \mathbf{B}_1 \cdot \boldsymbol{u}_1 + \mathbf{B}_2 \cdot \boldsymbol{u}_2 + \mathbf{Z} \cdot \boldsymbol{\kappa}. \tag{9}$$

The matrices in (9) are

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & v & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{B}_1 = \begin{bmatrix} L \cdot v & 0 & 0 & v \end{bmatrix}^T$$

$$\mathbf{B}_2 = \begin{bmatrix} \sin\alpha_{\text{ref}} & 0 & 0 & 0 \\ \text{a}_{\text{ref}} \cdot \cos\alpha_{\text{ref}} & 1 & 0 & 0 \end{bmatrix}^T,$$

$$\mathbf{Z} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^T.$$

IV. Experiment on a Simulator

This section presents the components of the test bench and the study design, in which the the benefits and usability of the LISC is analysed.

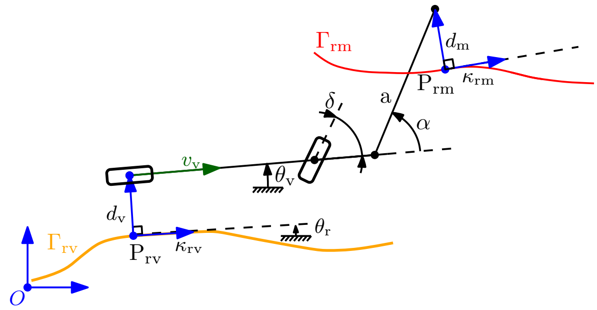

Fig. 2: The planar control model of the LVM [22]

A. Test-Bench

The test-bench consists of a steering wheel (Logitech - G29 Driving Force), a joystick (CLS-E Force Feedback Joystick, see [23]), a simulation computer and the graphical user interface (GUI). Fig. 3 shows a picture of this experimental setup. The test subjects can steer the vehicle with the steering wheel and control the manipulator with the joystick. A manual longitudinal control of the vehicle is not investigated in this study. The velocity control of the vehicle is fully automated with a constant speed. The software structure is given in Fig. 4.

The communication between the joystick and the computer happens with a manufacturer specific CAN protocol. The steering wheel sends the data via USB. On the simulator computer (Intel(R) Core(TM) i7-5930K CPU @ 3.50GHz, operating system: Ubuntu 18.04), a detailed real-time model of the LVM is simulated: The cylinders and manipulator models are based on [24] and the vehicle on [25]. For more details of the model implementations, we refer to [21]. The GUI shows the LVM from a bird's eye perspective, which is implemented with the Python Library *pygame*. In the scenario displayed on the GUI, the grey trajectory symbolizes the centre of the road and the blue boxes represent the areas to be reached with the manipulator.

B. Comparative Experiment Setup

The study is conducted by 14 test subjects (average age 27.64 years with the standard deviation of 3.10). The test subjects had the task to collect as many blue blocks as

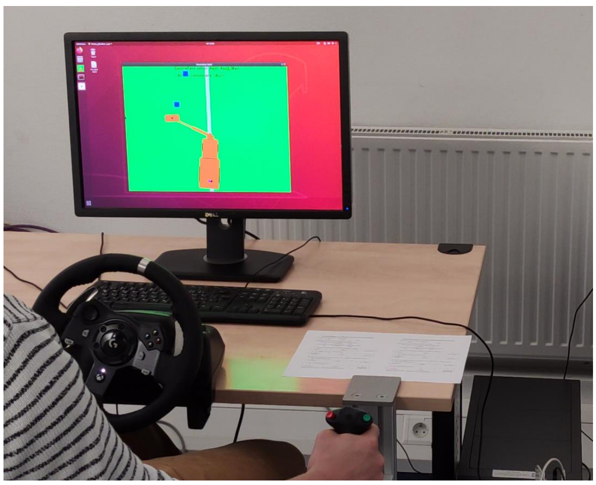

Fig. 3: An image of the test-bench with the GUI, steering wheel and joystick (bottom right).

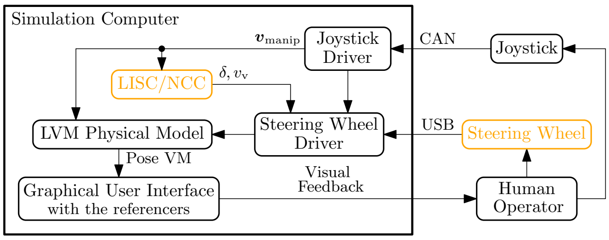

Fig. 4: The software structure of the simulator. The orange colour symbolizes the components realizing manual and automated modes for the different experimental runs.

possible. In manual mode, they had the additional task to keep the vehicle on its reference path. A longitudinal controller only keeps the vehicle's velocity constant $v_v = 1.25\,m/s$, which is typical value for mowing works.

Three lateral control modes are compared:

- Automation with LISC,
- Automation with an non-cooperative controller (NCC),
- Manual mode.

If the lateral controllers are active, the operator only has to control the manipulator and the vehicle guidance is autonomous. The procedure computing the feedback control laws are presented in detail in [6], here only the results are provided.

The NCC is the lateral guidance of vehicle without the consideration of the motion of the manipulator, which has the control law

$$\delta = -\mathbf{K}_{\mathrm{NCC}} \cdot [d_v,\, \Delta\theta_v] \tag{10}$$

where $\mathbf{K}_{\mathrm{NCC}} = [1.1,\, 3.2]$. This is analogous to the control of an autonomous vehicle or a wheeled robot.

The LISC has the structure of feedback control law as given in (6), where the extended system state is $\boldsymbol{x}_e = [d_v,\, \Delta\theta_v,\, \delta,\, \boldsymbol{x}_\kappa]$. The input of the LVM is computed by (7). The feedback gain is

$$\mathbf{K}_{\mathrm{LISC}} = [11.11,\, 25.32,\, 30.50,\, -29.01,\, -22.31]\,.$$

In the manual mode, there is no lateral guidance and the test subjects had to keep the vehicle on its reference. However, in some situations, they must prioritize whether to stay with the vehicle on the reference or collect the blue block. In these cases, they were told to leave the reference with the vehicle to reach the blue block. Important that they were allowed to leave the reference only to pick up the block and must return to the reference of the vehicle.

After these instructions, there was a approximately 5 minute long manual familiarization run. This long training run also tries to imitate that the test subjects have relevant experience and can perform the task as professionals, meaning that they can work well with the manual mode[2]. The familiarization part is not included in the evaluation. Then, the test subjects performed the three experimental runs, each with one mode, i.e. either one of the two controllers or in manual mode. They did not get any information, which of the two controllers (either LISC or NCC) is active. The order of the experimental runs was randomized. There was a questionnaire after each run, which was used to enhance test subjects' awareness and reflection on the different controller concepts. These questionnaire results were not used for the final evaluation. After finishing the three experimental runs, they were asked to fill the final questions which were applied for the subjective evaluation of the controllers.

[2]This procedure is valid because the goal of this study is to show that LISC can help even expert operators.

C. Objective Goals

With this study, the usability of the LISC is analysed: The central question is whether LISC can provide an improvement compared to the manual mode. Furthermore, the issue is addressed whether the proposed LISC can relieve the operator compared the manual mode or NCC. A direct comparison between the objective performance of NCC and LISC was already given in [6]. Two hypotheses are formed for the analysis:

H1 LISC leads to significantly better performance compared to manual operation.

H2 LISC provides a more intuitive control, eases the operator's workload and improves the sense of control over the task compared to NCC or to the manual operation.

As an objective measure of the operator's performance is chosen the number of collected boxes. Furthermore, the root mean square error of the average deviation from vehicle's reference

$$\overline{d}_{\mathrm{veh}} = \sqrt{\frac{1}{T_{\mathrm{end}}}\int_0^{T_{\mathrm{end}}} d_v^2(t)\,\mathrm{d}t}, \tag{11}$$

is evaluated. The subjective evaluation of the controllers are done by the final questions, which are:

Q1 I found the way of working with the controller ...
Not intuitive at all - 1 — Very intuitive - 7

Q2 I felt optimally (mentally) challenged.
(mental/cognitive strain).
Not appropriate at all - 1 — Very appropriate - 7

Q3 I had the feeling that I was in control of the process.
Not applicable at all - 1 — Very applicable - 7

Due to the uncertain information about the distributions, for the test of H1, a *Wilcoxon* rank sum test is applied [26]. This is less restrictive than the paired Student's t-test and its null hypothesis is that there is no difference between the medians of the two groups.

For H2, because all three samples are compared, the *Kruskal-Wallis* test is chosen for the statistical analysis [26]. The degrees of freedom of this test are $df = 2$ and the significance level is chosen to $\alpha = 0.01$. Its null hypothesis is that there is no difference between the three controllers. This hypothesis is declined if $\mathcal{H} \geq \mathcal{X}^2_{df,\alpha}$ holds, where $\mathcal{X}^2_{df=2,\alpha=0.01} = 9.21$.

V. Results

A. Objective Assessment

In Table I, the mean values and the standard deviations of numbers of collected blue blocks (Ncoll) with the three controllers are given. Beside these, the vehicle's average deviations from its reference $\left(\overline{d}_{\mathrm{veh}}\right)$ can be found in Table I. It is clearly noticeable, that most of the test subject collected the more blocks with LISC, meanwhile few of them achieved better or the same results with the manual operation. Furthermore, the box plots of the average deviations from vehicle's reference (11) are given in Fig. 5, which shows that all the test subjects have smaller average deviation with LISC compared to the manual mode. This means that collecting more blocks did not negatively influence the tracking of the vehicle's reference.

Applying the *Wilcoxon* rank sum test shows that these differences $\left(\text{Ncoll and } \overline{d}_{\text{veh}}\right)$ are statistically significant. The p-values are $p_{\text{H1}}^{\text{Ncoll}} = 3.88 \cdot 10^{-4}$ and $p_{\text{H1}}^{\overline{d}_{\text{veh}}} = 7.47 \cdot 10^{-6}$, thus H1 is accepted with the significance level of $\alpha = 0.01$.

Furthermore, the result from our earlier work [6] could be confirmed in this paper: Using the NCC, the test subjects collected less blocks compared to LISC. Applying, *Wilcoxon* rank sum test on LISC-NCC comparison, the resulting p-value is $p_{\text{LISC-NCC}}^{\text{Ncoll}} = 7.193 \cdot 10^{-6}$, confirming that this difference is significant.

B. Subjective Assessment

The results of the three questions of the subjective evaluation of the controller concepts are given in Table II. The LISC yielded better result compared to NCC or the manual mode. The null hypothesis of the test is declined regarding the intuition ($\mathcal{H}^{\text{Q1}} = 23.53$), the mental strain of the test subjects ($\mathcal{H}^{\text{Q2}} = 11.95$) and also the sense of control ($\mathcal{H}^{\text{Q3}} = 9.92$). Thus, the LISC provides significantly better results in all three aspects and H2 is confirmed.

C. Discussion

This study shows some interesting aspects, which are addressed in this subsection. The fact that LISC yielded better results compared to the manual mode is a promising result: It can ease the workload enabling the operators to concentrate better and fulfil his/her task more efficiently compared to the actual state-of-the-art.

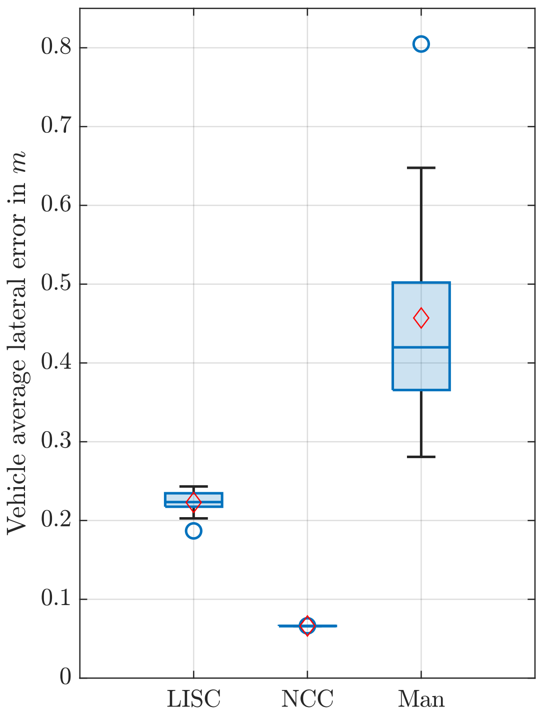

Fig. 5: Box plot of the average vehicle errors and deviations for the three different control modes (LISC, NCC, manual)

TABLE I: The mean values and the standard deviations of the collected block numbers with the two controllers and with the manual mode.

	LISC	NCC	Manual
μ_{Ncoll} [-]	114.64	79.43	98.50
σ_{Ncoll} [-]	2.44	5.26	14.79
$\mu_{\overline{d}_{\text{veh}}}$ [m]	0.223	0.066	0.457
$\sigma_{\overline{d}_{\text{veh}}}$ [m]	0.015	0.0	0.144

TABLE II: The mean values (and standard deviations) of personal questionary.

	LISC	NCC	Manual
Q1	6.21 (0.70)	2.79 (1.05)	3.43 (1.83)
Q2	5.71 (1.20)	3.64 (1.78)	3.50 (1.87)
Q3	6.07 (0.83)	3.43 (1.87)	4.36 (2.34)

A further interesting observation was that the test subjects collected less blocks with NCC than with the manual mode, meanwhile their subjective evaluation showed no significant difference between NCC and the manual mode, see Table I and Table II. This result indicates that a simple, classical automation of the vehicle reduces the performance. Thus, the use of the NCC is therefore not advisable for this application.

Fig. 6 compares the trajectories generated with LISC in comparison with manual mode trajectories. It can be seen that the test subject follows the vehicle's reference with manual mode less successfully. Furthermore, some of the blocks are missed with the manual mode, meanwhile all the blocks are collected with LISC. What is interesting is the fact that the trajectories of the vehicle are sometimes very similar. This indicates that the LISC can generate trajectories similar that are similar to human trajectories and therefore potentially intuitive to the human operator. Note that the proposed LISC does not aim to provide the same results as the manual mode. The goal is instead to relieve the human operator in challenging situations. It should be mentioned that the effects of the operators' environment perception can influence the controller's performance in real-world applications. Nonetheless, this simulator experiment validates the LISC concept and provides the strong indications that LISC can be considered in practical future projects with the manufactures of LVMs.

VI. Conclusion

This paper presents the practical validation of the proposed limited information shared controller for large vehicle manipulators. In this work, a comparison with the manual control is performed, which is the actual state-of-the-art for large vehicle manipulators. An experimental study with 14 test subjects was conducted on a simulator. The analysis shows that the proposed limited information shared controller helped the test subjects to better fulfill the manipulation task compared to the manual mode. The subjective assessment showed significant improvements using the proposed controller compared to the manual mode or the non-cooperative controller in all evaluated aspects: Intuition, mental strain and sense fo control. All together, it can be concluded that the work presented here validates the LISC concept.

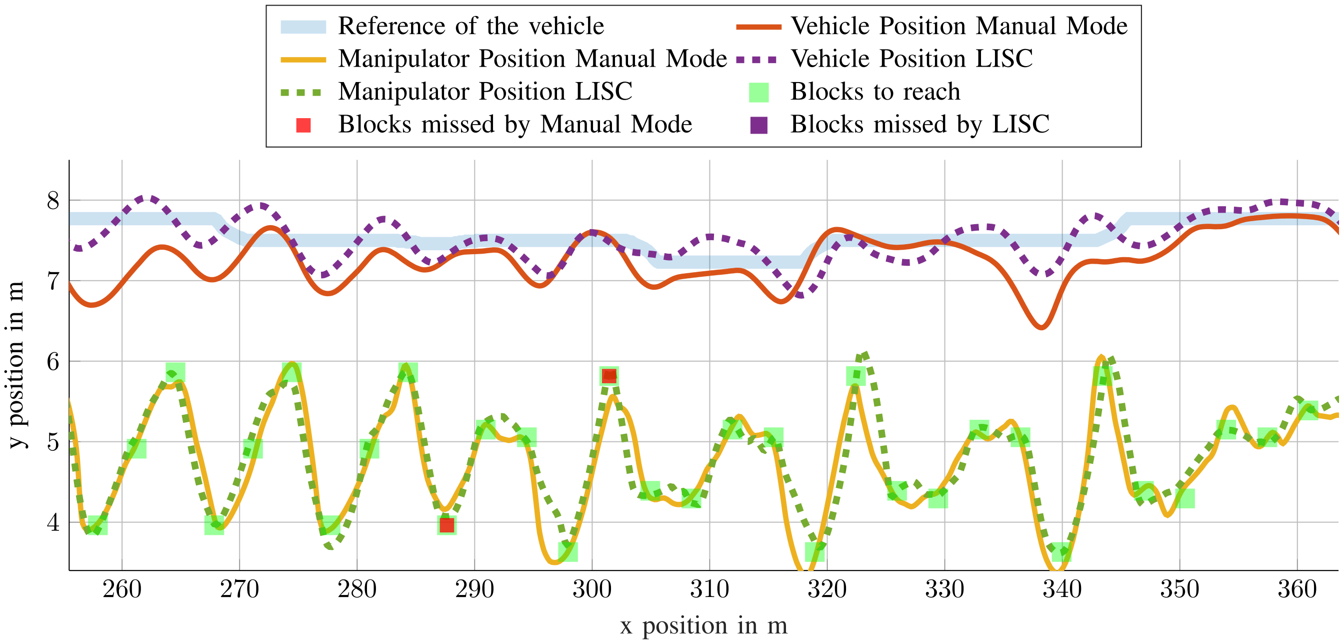

Fig. 6: Trajectories of the 5th test subject in manual mode and with the proposed LISC.

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