Assistance for Telepresence Using Online Grasp Planning

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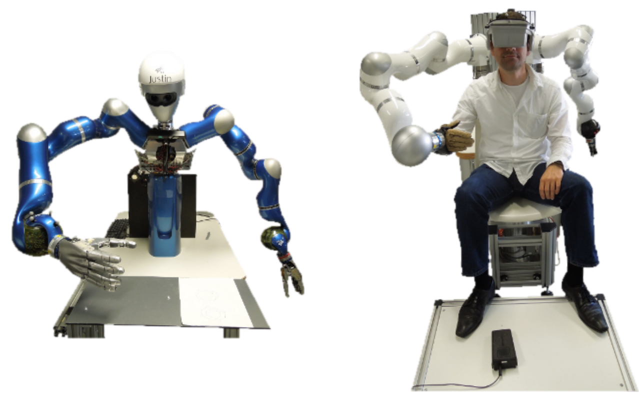
***Abstract*— This paper presents a user study evaluating teleoperated grasping performance and perceived workload of the human operator in a shared autonomy setup when working with different assistance modes and hand kinematics. The hands of a humanoid robot are operated using two approaches: direct mapping of human finger motions (telemanipulation), and "open/close" commands in combination with online grasp planning (shared autonomy). Human finger movements are measured with a data glove in both approaches. Grasp planning for the shared autonomy mode is based on the online calculation of reachable independent contact regions. In this approach, two visual assistance modes were tested: one indicating graspability in a binary manner (possible vs. impossible) and another one showing the potential contact regions for the fingertips. To analyze the influence of the hand kinematics on grasping performance and workload, two hands with different thumb positions are compared.**

The study shows that shared autonomy significantly decreases the task completion time and increases the grasp robustness compared to the direct mapping approach. The effect is more evident for a hand with optimized kinematics. The results reveal that choosing the appropriate control and assistance mode has a significant influence in telepresence performance.



(a) Remote Robot "SpaceJustin" (b) Master Station "HUG"

Fig. 1. DLR's telepresence system: the arms are position-force coupled and the finger movements are commanded by measurements with a Cyberglove.

I. Introduction

Telepresence systems are used to perform manipulation tasks in a remote environment by virtually immersing the human in that scenario. Application of telepresence systems includes the interaction with dangerous or inaccessible environments without the human being on-site, human training, or verification of the remote robots' abilities for certain tasks. In all these scenarios it is important to preserve and transfer the human's task knowledge, fine manipulation capabilities, and the ability to react fast and correctly to unexpected situations. Of course, this highly depends on factors like the capabilities of the remote robot, the coupling between master and slave, the mapping between human hand and the robotic end effector, or the feedback modalities used in the system.

Recently, shared autonomy (or semi-autonomous) systems have been developed, where the human operator is assisted with autonomous capabilities of the remote robot to compensate disadvantages of pure telepresence systems (bandwidth, time delay, or high workload of the operator) or limited capabilities of the input device or of the remote robot. Using a telemanipulation system without haptic feedback, seamless transitions between direct telemanipulation and semi-autonomous modes overcome limitations in bandwidth and time delay [1]. The autonomy mode is triggered when the remote robot is close enough to an object and a grasp is found. Visual interfaces that can be controlled by a computer mouse or a head tracker are cheap, popular and intuitive to use (everybody is trained to use a mouse), but are exhausting to control a robotic end effector with a high number of degrees-of-freedom. For instance, commanding a five-fingered hand involves positioning the hand in 6D and then commanding each finger separately to its desired position. The limited degrees of freedom of the input device and the typical 2D view of these interfaces can be compensated for by using more autonomy on the remote robot, e.g. [2], where it improves the performance of a mobile manipulation system using a two-fingered gripper in cluttered environments. A similar point-and-click interface has been used to compare grasping strategies for a two-fingered gripper switching from direct to supervisory control [3], thus avoiding collisions and improving efficiency. The context awareness of the human operator can be increased in such 2D scenes by capturing semantic information for the task and accordingly sorting a set of grasp hypotheses for the gripper. Such shared autonomy approaches combine the advantages of telemanipulation with the repeatability and precision of autonomous tasks, and considerably improve the performance of systems that do not use haptic feedback and where the user is not highly immersed in the remote environment.

Most of the shared autonomy approaches presented so far use neither an immersive environment nor a multifingered hand as end effector. This paper studies the influence of semi-autonomous subtasks on the performance of grasping with a complex end effector, with the human in the loop and immersed in the remote environment. For this work, DLR's telepresence system, shown in Fig. 1, is used. This system

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TABLE I
OVERVIEW OF EXPERIMENTAL CONDITIONS

Kinematic Setup	Thumb Configuration 1			Thumb Configuration 2		
Hand Control Mode	Direct Telemanipulation	Shared Autonomy		Direct Telemanipulation	Shared Autonomy	
Visual Assistance	None	Binary Assistance	Contact Regions Assistance	None	Binary Assistance	Contact Regions Assistance

and its predecessors were designed as on-ground verification testbeds for on-orbit servicing approaches and algorithms. The application of these systems to generalized maintenance or assembly tasks is documented in previous user studies, like [4], [5], and [6]. These experiments showed that all tasks were still feasible for untrained operators, even using a real geostationary relay satellite link for data transmission. Application to maintenance and industrial tasks in different scenarios has been demonstrated on trade fairs [7].

One main limitation when using complex telepresence systems is a major loss of dexterity [8]. Even if the input device can detect all the operator's movements, the robot system might not be able to follow all the commanded motions due to limited capabilities. The mapping between human hand and robotic end effector has to take into account the different manipulatory capabilities and kinematic configurations while providing the user with a natural interface. This is particularly crucial if the robotic end effector is not anthrophomorphic [9]. A shared autonomy framework that tackles the above described problems with a complex end effector was proposed in [10], which uses a low degree of freedom input device to trigger basic manipulation primitives for the Utah/MIT hand.

In this paper, we test the replacement of simplified gripping mechanisms like two-fingered grippers, mapped direct control of robotic fingers, or predefined primitives, with grasping methods that indicate robust fingertip grasps for a multifingered hand while keeping a low level of operator workload. In the current user study, a direct telemanipulation of a five-fingered robotic hand without any assistance is compared with a shared autonomy approach that uses two different visual assistance functions. The experimental conditions are shown in Table I. During the experiments, the human is always in control of the robotic arm to preserve the high immersion of the telepresence system. Grasping is performed in three modes:

1) direct control of the robotic fingers, no visual assistance
2) human can open and close, binary ("on/off") feedback
3) human can open and close, grasping regions are visible

Additionally, we study the influence of two different thumb configurations on the grasping performance. The first one provides a human-like configuration, but the second one generates a larger workspace. We analyze which thumb configuration provides a more natural interaction for the human for grasping tasks, considering the influence of the assistance modes on the perceived workload of the human operator and on the performance of fingertip grasping (measured with the time to completion and grasp stability).

The shared autonomy system is explained in detail in Section II, and the experimental setup is described in Section III. The results are presented in Section IV and discussed in Section V. Section VI concludes the paper.

II. SYSTEM OVERVIEW

A. The Telepresence System

The telepresence system consists of the multimodal human machine interface HUG [11] and the robot SpaceJustin (Fig. 1), which is a modified version of DLR's humanoid robot Justin [12]. The robot arms are position-force coupled, which allows the operator to command movements and to experience realistic force feedback in his palms [13].

The remote robot (Fig. 1(a)) has 17 degrees of freedom for torso, head, and arms, and interacts with the environment with two DLR-HIT Hands II [14]. HUG (Fig. 1(b)) is composed by two DLR Light Weight Robot arms mounted at a column behind the user, which allows him to use the complete workspace of his arms. In order to allow a high degree of immersion, the operator wears a head-mounted display showing the remote environment in 3D. His head movements are tracked and used to directly control the movement of SpaceJustin's head. The user wears a Cyberglove, and he is coupled to the robot arms with a magnetic clutch. The glove tracks the motion of the human fingers, which allows direct control of the fingers of the DLR-HIT hands via a Cartesian impedance controller.

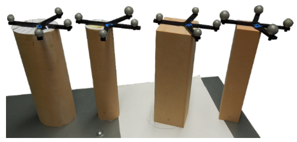
B. Semi-autonomous Grasping

This classic telepresence setup has been extended with shared autonomy for grasping ([13]) based on the calculation of reachable independent contact regions (rICR, [15]). The use of reachability information allows to plan grasps online based on the current relative pose between hand and object, while taking into account the hand kinematics in the computation. To make the approach more robust to errors in finger positioning, a target region (reachable independent contact region) is provided for each finger, which guarantees a force closure grasp if each finger is positioned inside its corresponding region. The desired position of each fingertip is calculated as the center of its rICR. The grasp quality is computed using the largest minimum wrench that the grasp can resist in any direction [16]. The human is always in control of the movements of the robot arm, and he also commands the closing of the robotic fingers by closing his

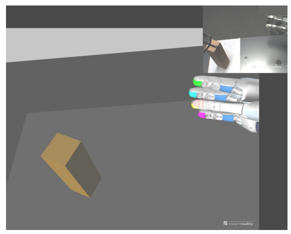
(a) Finger position at the beginning of each trial. It is also the “open” position in shared autonomy mode.

(b) Finger position to close the robotic fingers for grasping in shared autonomy mode.

Fig. 2. Open and Close Commands

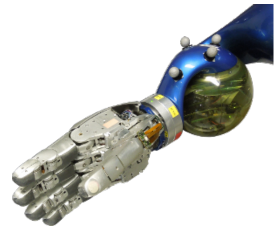


(a) Four objects with basic shapes to strengthen intuitive grasping.



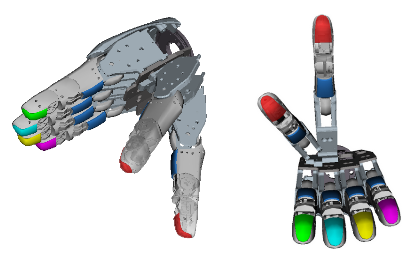
(b) View in head-mounted display: the virtual scene (large) is displayed in 3D, the camera stream of the real scene (small) is in 2D.

Fig. 3. Experimental Setup

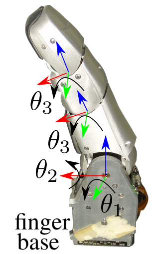


(a) Thumb configuration 1 looks more human like.

(b) Thumb configuration 2 provides a larger workspace.



(c) Comparison of the thumb configurations. The finger base can be mounted on the palm at two fixed positions.



(d) Schematic finger kinematics: the base is not movable and the last two links are coupled.

Fig. 4. Thumb Configurations

fingers (Fig. 2). Then, all robotic fingers move to the desired position on the object using Cartesian impedance control, and exert forces on the object in the direction of the surface normals to guarantee a firm grasp of the object.

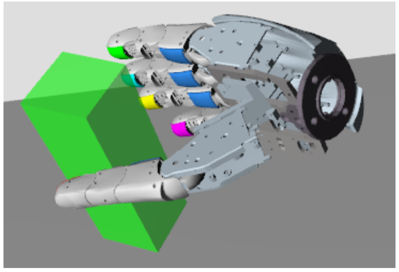
III. Experimental Setup

In the present user study, the participants use a simplified system setup of the shared autonomy system described above to shorten the exercise phase prior to the experiments: Only the right arm and hand are used to grasp objects, and SpaceJustin’s head is in a predefined position. This means that the viewpoint in the head-mounted display is fixed, to ensure comparability of the visual assistances between subjects and to reduce complexity of the test. The scenario is displayed in a virtual scene in 3D, and the stream of one SpaceJustin camera is shown in 2D, as illustrated in Fig. 3(b). We found this dual feedback very intuitive for the participants, like [2]. Both scenes provide the same viewpoint on the scenario. To avoid errors in object detection or the forward kinematics, hand and object positions are optically tracked with a camera system (A.R.T., [17]), the markers can be seen in Fig. 3(a), Fig. 4(a), and Fig. 4(b).

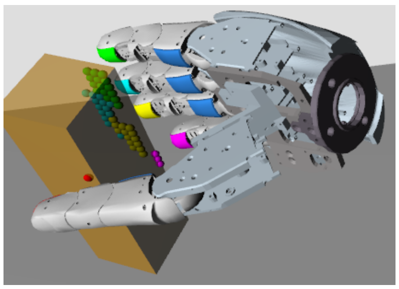
As described in Section II-A, the DLR-HIT Hand II is used as end effector of SpaceJustin. This five-fingered hand is modular, i.e. all fingers have the same kinematic configuration. Each finger has three links and four degrees of freedom (two of them coupled), as shown in Fig. 4(d). The base of each finger is mounted on the palm at a fixed position, and the abduction/adduction angle (θ_2) of the fingers can move between -15deg and 15deg. Consequently, the position of the finger base of the thumb has a large influence on the grasping performance of the hand. During several previous demonstrations of the telepresence system, human operators found the original position of the thumb (configuration 1, Fig. 4(a)) intuitive and easy-to-use, but they noted the small workspace of the hand. This workspace was increased by moving the thumb to a new position on the palm (configuration 2, Fig. 4(b)), which raised comments on the counterintuitive use of the hand, although the mapping between human and robotic finger movements was the same. Configuration 2 resulted in a higher number of failed grasp attempts. In this user study, the influence of the kinematics of the end effector on the perceived importance of assistance is taken into account by comparing these two thumb configurations (Fig. 4). Thumb configuration 1 is the original one, which looks more human-like, and configuration 2 provides a larger workspace, as the thumb opposes the middle finger and has an opening angle of 60deg.

In this study there were three assistance modes for grasping (Fig. 5):

- **No assistance**: No visual assistance is provided to the user. The user directly commands each finger of the robotic hand with the Cyberglove.
- **Binary assistance**: The object in the virtual scene turns green when the user can grasp the object, as illustrated in Fig. 5(a). The operator closes his thumb and index finger to initiate grasping, as shown in Fig. 2. The desired positions for all robotic fingers are provided by the rICR calculation (but the rICRs are not displayed).
- **Assistance with regions**: In this mode, the rICRs on the object are shown to the user, as illustrated in Fig. 5(b).



(a) Binary assistance: the object turns green if a force closure grasp is possible.



(b) Assistance with regions: the rICRs are displayed on the object, indicating the robustness of the grasp and the potential contact locations.

Fig. 5. Visual Assistance

When the operator is confident that the grasp is robust, i.e. the regions are large enough, he closes his fingers.

Although only one assistance mode displays the rICRs to the user, the evaluation of grasp quality and robustness is always based on the calculation of rICRs. The binary feedback mode also uses the grasp quality calculation of rICR, and when the grasp quality is larger than zero the object is graspable and shown in green.

Participants were instructed to grasp four objects with basic shapes: cylinders and cuboids, with a small and a large version of each, as shown in Fig. 3(a). The small cylinder is easier to grasp with thumb configuration 1, and the large cylinder is easier for configuration 2. The basic shapes were chosen to study the influence of assistance with objects that are intuitive to grasp. Nevertheless, the online grasp planning process can be applied to any arbitrary object represented as a point cloud [13], [15], so the results obtained with basic shapes are expected to be extrapolated to more complex and difficult-to-grasp objects.

Sample: Twenty participants were recruited from the student and staff population of the German Aerospace Center ($M_{\text{AGE}} = 28.4\text{yrs}; SD = 4.0; Md_{\text{AGE}} = 28.5\text{yrs}$). All subjects were right handed males with normal or corrected to normal vision. Participants read and signed a consent form prior to the experiment. Five of the 20 participants had experience in using HUG, but none in controlling the remote robot. Performance analyses revealed that previous experience had no influence on the performance of all five participants. The experience in CAD programs was also quantified (the question was: "I work with CAD programs on a regular basis", quantified in a scale from 1 to 7, where 1=Does not apply at all, and 7=Fully applies; $M = 3.6$, $SD = 2.5$). There was no statistically significant effect of CAD experience on the reported objective measures described in the next section.

A within-subjects experiment design with robotic hand (thumb configuration 1 vs. 2) and assistance (none vs. binary vs. grasping regions) as within factors was utilized, i.e., each subject executed six experimental conditions (Table I). The order of these conditions was randomly permuted to avoid potential time effects (like learning or fatigue).

Participants were informed about the experimental task and procedure. The hand/arm was controlled with the subjects' dominant hand, as shown in Fig. 1. In all conditions, individuals were told to grasp the objects from the side with the fingertips of the robotic hand, avoiding object and marker collisions when performing the task, and trying to perform secure grasps as quickly as possible. In each task block, subjects first completed a training trial grasping an object that was easy to grasp for the current thumb configuration, and then grasped the four objects in a row. Altogether, a number of 5 (1 training and 4 experimental trials) x 2 (thumb configurations) x 3 (assistance conditions) = 30 trials had to be completed. After each grasp, HUG was decoupled from the remote robot and SpaceJustin's arm lifted the object 0.1m straight up and rotated the object 30deg towards the thumb and 25deg forward to evaluate the stability of the grasp. After each assistance condition, subjects filled out the NASA-TLX questionnaire ([18], German version), and a questionnaire that included items on usability and interaction realism.

IV. Results

The assistance functions and robotic hands were evaluated using objective performance data and subjective user feedback, collected in questionnaires.

A. *Objective Data*

As objective performance indicators, we analyzed the time to complete (TTC) the tasks, average grasp quality, average size of rICR, overall finger movements, overall hand movements, and the results of the automatic grasp stability test (lifting and rotating the object) after each grasp. This section presents the results for TTC and the average grasp quality in detail. Size of rICRs is highly correlated to the grasp quality, so the results are not presented in detail. Section V discusses the results of the automatic test procedure; data from the overall hand and finger motion are used to support the discussion in that section.

Time to complete (TTC): A repeated measures analysis of variance (ANOVA) with *hand* (thumb configuration 1 vs. 2) and *assistance* (none vs. binary vs. contact regions) as repeated measures was performed on the TTC. A highly significant main effect of *hand* ($F(1, 17) = 10.9$; $p < 0.01$) occurred, revealing higher average TTC when performing the task with thumb configuration 1 (averaged across assistance modes, $M = (29.0\text{s} + 24.8\text{s} + 30.5\text{s})/3 = 28.1\text{s}$) compared to thumb configuration 2 (averaged across assistance modes, $M = (28.8\text{s} + 16.6\text{s} + 18.0\text{s})/3 = 21.1\text{s}$) as

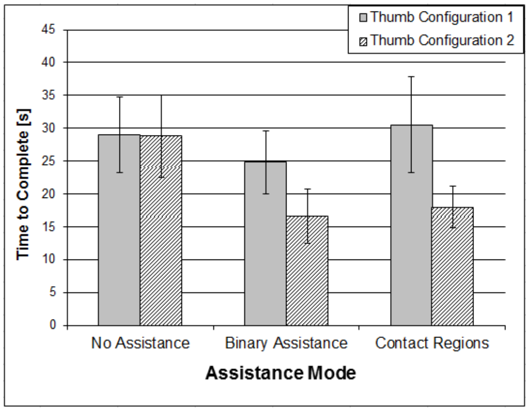


Fig. 6. Time to Complete the Tasks: significant reduction in TTC for thumb configuration 2 (both assistance modes), for configuration 1 there is a recognizable trend towards reduction of TTC with binary assistance.

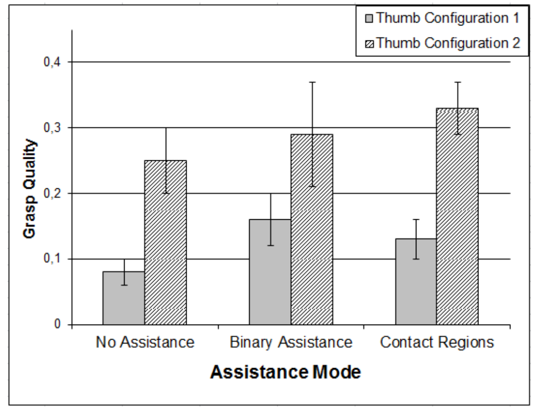


Fig. 7. Grasp Quality: both visual assistance modes increase the grasp quality for both thumb configurations. The influence of assistance with contact regions is larger on the grasp quality for thumb configuration 2.

shown in Fig. 6. A more detailed discussion of this result follows in Section V. Moreover, a highly significant *assistance* main effect ($F(2, 16) = 10.7$; $p = 0.001$) indicates significantly shorter TTC in the binary assistance condition ($M = 20.7$s) compared to conditions without assistance ($M = 28.9$s; $t(18) = 3.93$; $p < 0.001$). Yet, a significant two-way interaction effect *hand* x *assistance* ($F(2, 16) = 4.9$; $p < 0.05$) revealed that the positive effect of assistance conditions is stronger when using thumb configuration 2. In this case, TTCs were significantly shorter when having binary ($M = 16.6$s) or contact region assistance ($M = 18$s) compared to the conditions without assistance ($M = 28.8$s; both $ts(18) > 3.7$ and $ps < 0.01$). No significant difference between both assistance conditions was found ($t(18) = 0.7$; not significant (ns).).

Grasp quality (*100): Next, we analyzed the variance of the average grasp quality. Repeated measures ANOVA performed on the grasp quality revealed a highly significant *hand* main effect ($F(1, 17) = 45.2$; $p < 0.001$), with better results for thumb configuration 2 ($M = 0.29$) than for configuration 1 ($M = 0.12$), as shown in Fig. 7. Additionally, a significant *assistance* main effect ($F(2, 16) = 10$; $p < 0.01$) indicated low grasp quality without assistance ($M = 0.16$), and better quality with binary assistance ($M = 0.23$) and contact regions assistance ($M = 0.23$). Again, a significant two-way interaction effect *hand* x *assistance* occurred ($F(2, 16) = 4.1$; $p < 0.05$), i.e. grasp quality was significantly better when working with the contact regions and thumb configuration 2 compared to thumb configuration 1.

Grasp Evaluation: Repeated measures ANOVA revealed no significant effect (all FS $<$ 2.2). Interestingly, however, the grasps were stable in 100% of the cases when using thumb configuration 1 and contact regions assistance, while the corresponding value for configuration 2 was $M = 92\%$.

B. Subjective Data

Besides the objective measures, participants answered questions regarding their workload, the assistance functions and the naturalness of the interaction with the robotic hand:

Workload: A repeated measures ANOVA on the NASA-TLX overall score (scale ranging from 0-20) revealed no *hand* condition main effect ($F(1, 20) = 1.8$; ns.), but a highly significant *assistance* condition main effect ($F(2, 19) = 14.3$; $p < 0.001$). For both thumb configurations we found significantly lower workload scores for the binary feedback conditions ($M_{\text{hand},1} = 6.5$; $SD_{\text{hand},1} = 3.2$; $M_{\text{hand},2} = 5.7$; $SD_{\text{hand},2} = 3.0$) and the contact region conditions ($M_{\text{hand},1} = 6.9$; $SD_{\text{hand},1} = 3.0$; $M_{\text{hand},2} = 5.6$; $SD_{\text{hand},2} = 3.2$) compared to the no assistance conditions ($M_{\text{hand},1} = 8.3$; $SD_{\text{hand},1} = 3.6$; $M_{\text{hand},2} = 8.4$; $SD_{\text{hand},2} = 3.7$; all $ts(20) > 2.2$; $ps < 0.05$). This effect was particularly evident when working with thumb configuration 2 (both $ts(20) > 4.7$; $ps < 0.001$). The average workload scores in the binary feedback and contact regions condition do not differ significantly (both $ts(20) < 0.9$).

Assistance functions: Participants had to answer the following question: “Even before completing the grasp I was sure that I would securely grasp the object ”. The answers were quantified with a 7-point Likert scale, where 1=Does not apply at all, and 7=Fully applies. When working without assistance function, significantly lower ratings were reported ($M = 2.3$; $SD = 1.0$) compared to binary ($M = 5.0$; $SD = 1.4$) and contact regions assistance ($M = 5.8$; $SD = 1.1$; both $ts(19) > 6.4$; $ps < 0.001$). Moreover, ratings in the contact regions conditions were significantly higher than in the binary feedback condition ($t(19) = 2.2$; $p < 0.05$). Seemingly, the binary assistance does not give enough information about possible grasps: “When working with binary feedback there were situations in which I did not know how to modify the hand position to find an optimal grasp”, $M = 4.0$; $SD = 1.8$.

Interaction with robotic hands: First, we asked about the interaction with the robotic hand and the virtual scene: “How natural was the interaction with the robotic hand in the virtual environment?” (1=Very unnatural; 7=Very natural). Ratings for thumb configuration 1 ($M = 3.9$; $SD = 1.4$) and configuration 2 ($M = 4.5$; $SD = 1.6$) did not differ significantly ($t(19) = 1.6$; $p = 0.12$). Next, we asked individuals to which degree they felt that their motions were restricted when using the different thumb positions of the robotic hand: “I felt severely restricted by the thumb position during interaction with the objects” (1=Does not apply at all; 7=Fully applies). Subjects reported that they felt significantly more restricted by thumb position of configuration 1 ($M = 4.5$; $SD = 1.8$) compared to configuration 2 ($M = 2.4$; $SD = 1.0$; $t(19) = 5.2$; $p < 0.001$). Moreover, the initial training period seemed to increase confidence on the thumb configuration 2: “After a short period of training, I no longer worry about the thumb position”. Ratings were significantly higher for configuration 2 ($M = 5.5$; $SD = 1.2$) compared to configuration 1 ($M = 4.3$; $SD = 1.7$).

V. Discussion

Both objective measures revealed a better performance of grasps with assistances for both thumb configurations. Overall there was no significant difference between the two assistance modes, although people felt more secure when being assisted with the contact regions. Moreover, the assistance effect was stronger for thumb configuration 2. This can be explained by the larger workspace and the less anthropomorphic thumb position of configuration 2: the wide opening angle between thumb and palm makes it less natural to interact with, so the user needs to rely more on the assistance. Yet, the assistance showing the contact regions leads to a slightly higher TTC than with binary feedback. As the contact regions give a detailed description of the robustness of the grasp, the higher TTC results in grasps with higher grasp quality for configuration 2, where human intuition is not so helpful as the configuration is not anthropomorphic. Overall, thumb configuration 2 leads to a reduction of TTC and to an increment in grasp quality when compared to configuration 1.

Comparing the thumb configurations, we noticed that the grasp quality for configuration 1 decreases and the TTC increases when using the assistance with regions (compared to the binary assistance). This can be induced by the limit on the abduction/adduction angle. In configuration 1 the whole hand needs to be moved for opposing the thumb to the other fingers in order to achieve a robust grasp that cannot be obtained by purely moving the thumb to its lower joint limit, thus requiring an additional hand rotation. This fact was empirically verified when comparing the overall rotational movement of the hand between the thumb configurations; the users rotated more the hand with thumb configuration 1 than with configuration 2. Additionally, one could observe that the participants rotated the hand more when using binary assistance, as they had no information on “how close” they were to a valid grasp. The display of the rICRs caused the feeling of “being close to a good grasp”, and people usually relied more on translational exploration (rather than rotational exploration) to improve the grasp, which resulted in a higher TTC and often in less stable grasps. The contact regions improve the transparency and confidence on the system, as indicated by the participants, while the additional visual information does not result in higher workload compared to a simpler on/off visualization.

Although there was no difference in TTC without assistance between both thumb configurations, participants felt that their movements were more restricted by thumb configuration 1. As thumb configuration 1 looks more human like, we expected people to operate that hand more intuitively, which was not confirmed in the subjective data. Reactions on the thumb positions included: Thumb configuration 1 is “more intuitive but with smaller workspace” and “the opening angle is too small”. Configuration 2 is “less intuitive to control”, “the thumb has an unnatural position, but after some training is easier to handle”, “small objects are hard to grasp”, and “the larger opening angle of the thumb is helpful”.

Regarding the views in the head-mounted display showing the real scene and a virtual scene, we found out that participants relied mostly on the real scene when no assistance was provided (even though it was displayed only in 2D). When using the binary assistance mode, their focus changed between the two scenes, and their attention switched mostly to the virtual scene when using the contact regions.

The automated test for grasp stability revealed no significant effects, sometimes objects fell out of the hand or changed the pose inside the hand in all the experimental conditions. This happened three to five times out of 160 grasps per each assistance mode. In telepresence mode with no assistance, haptic feedback could help to assess the stability of a grasp; however, we did not use haptic feedback for the fingertips in the experiment, so participants could not experience the grasp forces. Also, with no assistance the users sometimes grasped objects with a poorly positioned thumb, which resulted in unstable grasps. We observed additionally that poor fingertip grasps sometimes moved the object within the hand producing very stable power grasps (although the intention was to make a precision grasp). In the cases where assisted grasping failed the test, it was mainly due to two reasons: tracking errors and torque limits in the thumb. Due to the modular hand design, the thumb has the same motors as the other four fingers. As the calculation of rICRs does not consider the dynamics of the fingers, the thumb sometimes could not exert enough forces on the object, and the object was dropped during the stability test routine. This happened especially for thumb configuration 2, as the thumb has to travel more space to reach the object surface.

VI. Conclusions and Future Work

This paper presents a user study that analyzes the effect of direct telepresent control vs. visual assistance on the grasping performance in a shared autonomy setup. Users unfamiliar with the shared autonomy system operated a remote robot using a human-machine interface and a Cyberglove. Two different thumb configurations of the DLR-HIT Hand II were used. Thumb configuration 1 is the original thumb position of the commercially available model, and configuration 2 provides a larger workspace by a change in the thumb position. Users were asked to grasp four objects while using three different assistance modes: no assistance, binary assistance and assistance with contact regions. In general, grasping was faster and had higher quality when using the assistance modes, and the results were more evident for thumb configuration 2. Although objective data did not show a difference between both assistance modes, participants reported to feel more confident with contact regions assistance.

The test was carried out with four simple objects. However, we expect that the conclusions can be extrapolated and that the virtual scene and assistance modes will be even more helpful with complex objects or in cluttered environments.

In the present study, available workspace of the hand configuration and hand anthropomorphism were mixed. In future studies, it would be interesting to disentangle the influence of both aspects on the grasping performance and user experience. Moreover, users had two different visual channels: the real and the virtual scene, which might have been confusing and caused attentional switching costs. Thus, a mixed reality approach would be a promising approach for future developments.

VII. Acknowledgment

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