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Efficiency based modulation for wheelchair driving collaborative control

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Abstract— **This work presents a new approach to shared control to assist wheelchair driving. Rather than swapping control from human to robot either by request or on a need basis, the system estimates how much help is needed in a reactive fashion and continuously produces an emergent motory command in combination with human input. To provide time stability and integration, instant commands are modulated by a factor depending on human efficiency in a shifting time window. Thus, the better the person drives, the more control he/she is awarded with. The approach has been tested at Fondazione Santa Lucia (FSL) in Rome with volunteers presenting different disabilities. All volunteers managed to finish a mildly complicated trajectory with door crossing and major turns and the proposed system increased efficiency in all cases.**

I. INTRODUCTION

In nowadays aging society, persons with disabilities may require some assistance to remain autonomous. Mobility, in particular, has been a main concern leading to robotic wheelchair solutions. These wheelchairs are expected to assist persons in maneouvres they can not do on their own, but not supposed to take full control on mobility, as this is reported to lead to loss of residual capabilities and frustration. Indeed, researchers favor shared control approaches, so that the wheelchair just provides the required amount of help.

There are many studies on the level of autonomy a robot might have when interacting with a human and viceversa [1] [2] [3]. Depending on *how* much autonomy the machine has, collaborative approaches can be roughly categorized into i) safeguarded operation; and ii) shared control. In the first case mobiles are totally under human control, except in danger [4] [5] [6]. In the second case, control is switched from user to machine depending on the situation at hand. Some approaches [1][3][7] [8] [9] [10] rely on a basic set of primitives like $AvoidObstacle$, $FollowWall$ and $PassDoorway$ to take over in difficult maneuvers, either by manual selection or automatic triggering. In other cases, a subsumption like scheme [11] is used: events trigger one or several behaviours which are merged into an emergent one. In extreme, persons might only point a target and the machine works like an autonomous robot, usually via a hybrid navigation scheme [12][13] [14] [15] [16] [17].

In previous works [18][19][20] the authors proposed a new approach to collaborative control. It consisted of locally evaluating the performance of the human and robot alone at each time instant. Their resulting efficiencies were used as weights to combine their commands in a reactive, emergent way. This approach is briefly presented in section II. However, this approach led to some local oscillations in areas where persons changed their minds often (typically complex areas) or the robot algorithm did not perform so well (doors and narrow spaces). This problem was intrinsic to the purely reactive nature of our approach, but can be solved by means of some temporal inertia. A new system, based on efficiency modulation via an envelope, is described in section III and results with volunteering in-patients in Fondazione Santa Lucia (Rome) are presented in section IV. Finally, section V presents conclusions and future work.

II. COLLABORATIVE NAVIGATION SYSTEM

One of the main advantages of reactive navigation schemes are that they may deal with several sensors and goals in a simple way. Thus, we use them to combine human and wheelchair commands and goals. Since humans tend to have a deliberative agenda that is propagated down to joystick commands, they provide some global efficiency and usually avoid local traps. Robot control may also include a deliberative layer to work in a hybrid way for persons presenting cognitive disabilities. In that case, high level control would simply decompose the trajectory into a set of consecutive local targets [18], but the system would use a purely reactive approach to reach each in a sequence.

The reactive system is based on a pure Potential Fields Approach (PFA) [21]. PFA basically rely on modelling obstacles as repulsors and goals as attractors to create a vector field that returns a motion vector at each point. PFA provides a simple and efficient tool for autonomous motion that, in its simplest version, has been reported to present some problems due to their reactive nature: i) oscillations when obstacles are too close; ii) incapacity to move safely through narrow corridors; and iii) local traps. Basically, the user provides a direction (e.g. via a joystick), which is added as another vector to the potential field at each time instant (Fig. 1). The key to our collaborative scheme is to determine how to weight human and robot vectors to preserve efficiency and safety and, yet, allow the user to be in control all the time. Specifically, weights are proportional to the efficiencies of human and robot at each instant. Usually, robots will be more precise, whereas humans will be more versatile.

Efficiency (η) needs to be locally calculated due to the purely reactive nature of the approach. We have found three local factors to have an immediate effect on navigation (Fig. 1): *Smoothness* (η_{sf}), *Directiveness* (η_{tl}) and *Safety* (η_{sc}), each ranging from 0 to 1. Smoothness reflects how sharp

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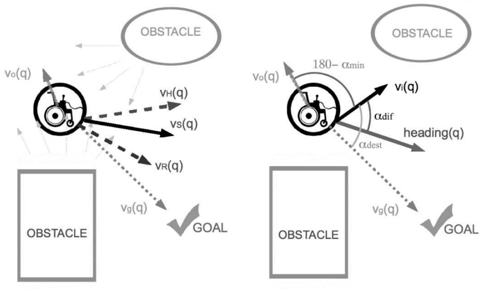

(a) (b)

Fig. 1. a) Vectors involved in motion command calculation; and b) local efficiency factors for an agent i.

direction changes are undesirable for driving. Safety reflects that it is better to keep away from obstacles. Directiveness tries to reflect that moving ahead to the goal in a straight way leads to shorter paths.

Smoothness (η_{sf}) is locally evaluated as the angle between the current direction of the robot and the provided motion vector. This factor is included because mobiles may be non-holonomic, meaning that they can not change directions abruptly due to their kinematics. Consequently, it is better to change heading as less as possible to avoid slippage and oscillations. *Directiveness* (η_{tl}) is locally measured in terms of the angle formed by the robot heading and the direction towards the next partial goal provided by the global planner. Obviously, the shortest way to reach that goal is to go straightly towards it, consequently making the angle zero. Obviously, any obstacle in the way would prevent that movement, but this is contemplated by another factor. *Safety* (η_{sc}), is evaluated in terms of the distances to the closest obstacles at each instant with respect to the heading direction. The closer the wheelchair gets to obstacles, the less safe the trajectory is.

$$\eta_{sf} = e^{-C_{sf}\cdot|\alpha_{dif}|} \tag{1}$$

$$\eta_{tl} = e^{-C_{tl}\cdot|\alpha_{dest}-\alpha_{dif}|} \tag{2}$$

$$\eta_{sc} = 1 - e^{-C_{sc}\cdot|\alpha_{min}-\alpha_{dif}|} \tag{3}$$

η_{sf} is smoothness, where C_{sf} is a constant and α_{dif} is the angle difference between the current direction and the command vector. η_{tl} is directiveness, where C_{tl} is a constant and α_{dest} the angle between the robot heading and the direction towards the next partial goal. η_{sc} is safety, where C_{sc} is a constant and α_{min} is the angle difference between the current direction and the direction of the closest obstacle. C_{sf}, C_{tl} and C_{sc} are used in these equations to balance the impact of local efficiencies on global performance, so that one or other decreases faster to reflect that the environment is more sensitive to that particular factor. In our case, we set them all to 1 so that all factors are equally important. Finally, efficiency is obtained through the average of the three aforementioned factors.

This approach has proven to work well with volunteering in-patients presenting different degrees of disability in Fondazione Santa Lucia [20][19]. All volunteers increase their performance when they use this collaborative scheme. In some cases, persons with significant cognitive problems required, as commented, a deliberative layer to suggest a trajectory for them. However, some problems arisen when disabilities were too remarkable. In these cases, assistance provided might not be enough to solve complex situations, as the person's contribution might even be having a negative effect on the emerging command. Furthermore, when persons have a punctual error in their driving, they are immediately compensated by the machine in a somewhat brusque way. We have observed that this may lead to a struggle between person and robot for people with minor disabilities, when they acknowledge the robot's contribution. Some temporal inertia helps to solve this problem.

III. EFFICIENCY BASED CONTROL MODULATION

Given the PFA rotational (v_{rR}) and translational (v_{tR}) velocities and the human ones (v_{rH} and v_{tH}), shared motion velocities, v_{rS} and v_{tS}) are defined as:

$$v_{rS} = (1-K)\cdot\eta_R\cdot v_{rR} + K\cdot\eta_H\cdot v_{rH} \tag{4}$$

$$v_{tS} = (1-K)\cdot\eta_R\cdot v_{tR} + K\cdot\eta_H\cdot v_{tH} \tag{5}$$

where η_R is the efficiency of robot motion commands and η_H is the efficiency of human motion commands. Both robot command and human input are added as weighted vectors (Fig. 1), so that persons receive more control as a reward for a better efficiency. Shared motion command efficiency is defined as η_S. Efficiencies range from 0 to 1, being 1 the maximum efficiency. It must be noted that η_S is not equal to η_R nor equal to η_H. In most cases, it will tend to the average η_R and η_H. In this case, we have added a new variable K to modulate the contribution of human and machine in an envelope way. K is calculated as:

$$K = \frac{\sum_{i=t_{dis}}^{t}\eta(i)}{t-t_{dis}} \tag{6}$$

t_{dis} being the last time instant before t in the trajectory where K showed a clear inflection point.

The effect of this time window is fairly intuitive: basically, steady changing efficiency is related to motion in difficult areas, where we want assistance to increase or decrease quickly. Punctual efficiency changes, though, correspond to local errors, that should not be reflected in the amount of assistance provided. The length of the window is basically controlled by how much K is holding in average with an acceptable variation.

Using this formula, we could have a continuous variation of K, but doctors requested us to have just three values: 0.75, 0.5 and 0.25, corresponding to human higher control, equal contribution and machine predominance. The values are chosen according to the following criteria:

- If $(\bar{\eta_H} > 0.85)|(\bar{\eta_H} > 1.5\cdot\bar{\eta_R})$, meaning that either the person is doing very well or, at least, clearly outperforming the machine, $K = 0.75$.

- If $(\bar{\eta_H} < 0.85)\&(0.5 \cdot \bar{\eta_R} < \bar{\eta_H} < 1.5 \cdot \bar{\eta_R})$, $K = 0.5$.
- Else, $K = 0.25$.

IV. EXPERIMENTS AND RESULTS

The proposed system was built on CARMEN (Collaborative Autonomous Robot for Mobility ENhancement), a modified a Runner Meyra wheelchair, donated by Sauer Medica S.L., adding odometry and a frontal Hokuyo laser URG04-RX for localization and obstacle detection. We included a PC that received joystick commands and, after combining them with the reactive ones, sent the emergent orders to the motors.

A. EXPERIMENTAL SETUP

This system was tested with volunteering in-patients in FSL, more specifically in Casa Agevole (http://www.progettarepertutti.org), a standard compliant test house in the complex. All tests were performed under direct supervision of FSL medical staff, approved by FSL Ethical Committee and performed with volunteers' consent. FSL staff provided disability indexes for these in-patients. Specifically, performance was measured with the metrics in [20]: *Smoothness*, *Directiveness* and *Safety* for efficiency, *Intervention level*-percentage of time that the user operates the joystick-, *Disagreement*-angle between joystick command and wheelchair heading- and *Joystick Variation*-number of joystick changes larger than 5%- for stress, effort and frustration, *Inconsistency* for cognitive skills, and path *Length*, *Curvature* and *Completion Time* for performance. Among other metrics, in-patients were profiled via the *Barthel* and *MMSE* (see [20]) indexes for physical and cognitive abilities, respectively.

The proposed trajectory was a complex one: volunteers had to enter the house via the front door, followed by a narrow corridor. At their chosen point, they had to U-turn left, after leaving a cupboard on the right and always paying attention to the right wall. Then, facing the opposite side in the side room, they had to move out of the house via a second door. The room for maneouver was quite restricted, but typical homes are usually like this, so it was interesting to check what happened in reality-like conditions. Fig. 2 show some captures of a random volunteer at key locations of the proposed path. It can be noted that there are no signals on walls or floor and general guidelines could only be provided at the beginning of the test, like "enter the house by this door and get out by the other one". It is also important to note that moving backwards is not allowed, so turning too late in the trajectory may end up in a stuck-up situation. In this experiment, the system does have a deliberative layer [22]that usually provides three local targets, approximately marked in Fig. 2 at the end of the three arrows. However, since it recalculates paths on a need basis, their locations may change and even additional local targets might appear if necessary.

B. CASE STUDY: INPATIENT 2

First, we present an example with volunteer 2, a 68 years old lady affected by Spinal cord injury. She has been chosen because she was already a volunteer in the previous tests, 5 months before, when modulation was still not used, In her first tests in February 2009 she could not walk, but in June 2009 she could walk with the help of a walker. In the new tests she had an MMSE index equal to 29.4, over 30, where 26 is accepted as average dementia threshold. Hence, she has no cognitive disabilities. Her Barthel index grew from 49 to 86 (over 100) in 5 months, meaning that she recovered many physical skills. Indeed, this time, she performed clearly better than in February, where she had trouble with turns and managed to finish only one of three runs. K was not variable at the time, so February tests could be understood as a fixed K=0.5 case.

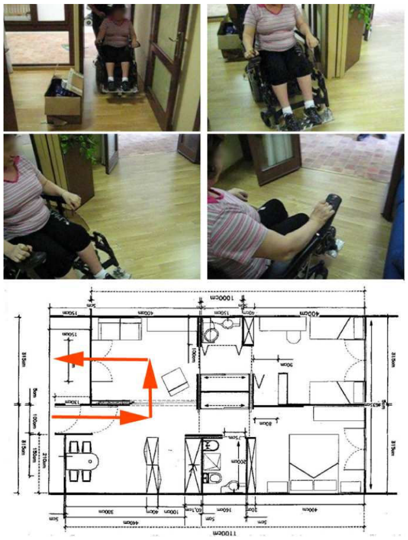

Fig. 2. Tentative path for experiment in Casa Agevole.

The path in February was approximately reverse to the one in Fig. 2, but it stopped before crossing the narrow door. Fig. 3 presents some results from February tests: a standalone benchmark run and a collaborative run. In the first case, the person received no assistance (except for a safeguard mechanism that stops the wheelchair in case of imminent collision). In the second case, the increase of efficiency at each point of the trajectory is overprinted in bright green over human performance. It can be observed that, despite the significant increase in efficiency, in this case the person was not capable of U-turning, mostly because she had severe complications with turns. It can be observed that efficiency is represented in RGB in the graphs, where R, G and B correspond to Smoothness, Directiveness and Safety respectively. Thus, pink areas correspond to lack of green (Directiveness), whereas blue ones lack Smoothness as well. This allows visual intuitive interpretation of results. For example, in the case in Fig. 3 it can be observed that delay in turning right leads to sharp oscillations to correct the trajectory but, nevertheless, the lady fails to prevent the wheelchair from getting stuck too close to a cupboard. In the second case, collaborative control avoids some oscillations (see non-blue plot color), but assistance is not enough to correct the trajectory and avoid stucking up as well. Table I briefs efficiencies in these tests in February.

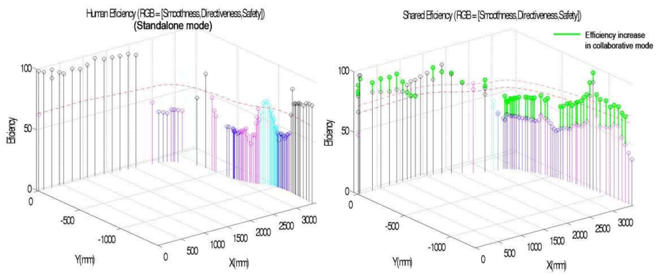

Fig. 3. Tests February'09 (K=0.5): a) standalone; b) collaborative mode.

It is important to note that in collaborative mode, human actions also have an impact in robot efficiencies, as the robot is not free to operate on its own. This impact could be positive (e.g. to avoid oscillations at doors) or negative, as smoothness will be affected by continuous compensation of the person's trajectory. Thus, it can be observed that robot smoothness is not that good despite the benefits of a PFA. Smoothness could be improved by using a more efficient reactive algorithm, but this would mean decreasing human control, and this was undesirable. Yet, as this person has difficulties to turn, her worst feature is Directiveness.

Test number		Feb'09	Feb'09	Jun'09
Control type		Standalone	Shared (K=0.5)	Shared (Kvar)
Global efficiency (%)	Robot	61.08	58.77	70.07
	Human	63.78	62.49	64.63
	Both	63.95	68.07	72.59
Smoothness (%)	Robot	49.06	42.31	51.15
	Human	54.88	73.57	63.18
	Both	55.09	66.2	67.93
Directiveness (%)	Robot	43.39	48.51	67.77
	Human	42.66	21.48	33.48
	Both	42.65	41.96	52.99
Safety (%)	Robot	90.88	85.69	91.29
	Human	94.07	92.66	97.18
	Both	94.2	95.99	96.88
Intervention Level	%	99.56	90.94	93.68
Disagreement	%	28.15	39.08	22.97
	dev	21.69	22.27	17.9
Joystick Variation	%	0.08	0.07	1.61
	dev	1.29	1.18	6.36
Inconsistency	%	4.19	7.11	8.37
	dev	4.19	7.11	9.45
Total Length	m	4.33	5.43	9.45
Total Curvature	degrees	101.1	128.8	175.06
Curvature	mean	0.01	0.01	-0.13
	dev	1.07	0.12	0.3
Completion time	sec	22.11	31.25	55.62

TABLE I
IN-PATIENT 2 DATA

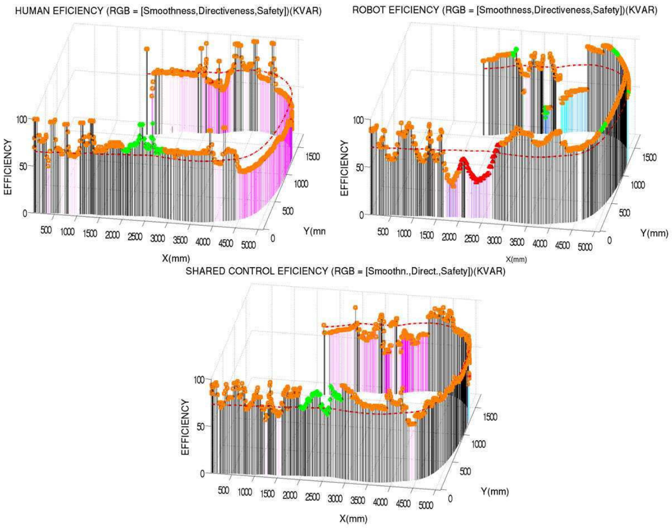

Fig. 4. Efficiencies for human, robot and shared control with adaptive envelope.

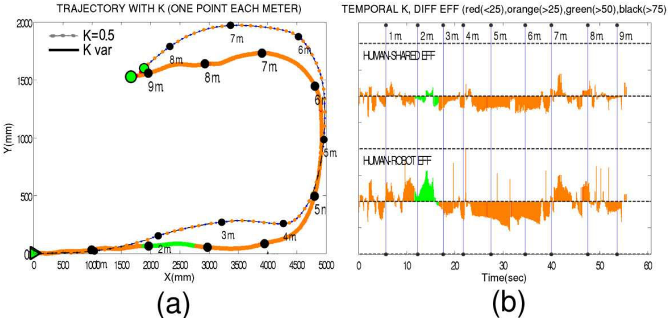

Fig. 5. a) Trajectories for K variable and K equal to 0.5; b) Substraction between and human-shared and human-robot efficiency for adaptive K.

After experiments in February, we checked that almost every fail in finishing the trajectory for volunteers could have been avoided if more assistance have been temporarily provided on a need basis, so we checked the proposed algorithm in our new tests. In-patient 2 physical skills were significantly improved in June, still, we checked that assistance improved her performance. Furthermore, she reported to be pretty comfortable with the wheelchair this time. Fig. 4 shows inpatient 2 efficiencies in this new try, the robot and collaborative control respectively. We use the same color code, only the top of each efficiency value is colored green, orange or red for K equal to 0.75, 0.5 or 0.25, respectively. For example, it can be observed that there is a narrow area where PFA oscillations make K_{human} go green and K_{robot} go red (hence, a green K=0.75), as the person outperforms the robot for a while. At the second turn, it can be observed that the person turned late (loss of Directiveness) and the robot provoked a sharp turn (light blue area) to compensate. Yet, this time the person did not receive a higher K because her Directiveness had been consistently low in the most recent path section. Fig. 5.a shows the different trajectories achieved in June tests by inpatient 2 for K fixed to 0.5 and adaptive K. It can be observed that the correction in the green K area allows a shorter, more efficient trajectory in this try. In Fig. 5.b we can observe how human control is clearly closer to collaborative one than to the robot's, specially in areas with high K values.

Naturally, in-patient 2's ability to U-turn in June is not simply due to our new approach, but rather to her rehabilitation therapy in the hospital. Still, it can be checked that the system works as expected and this person reported to feel more comfortable with it this time. Nevertheless, it is interesting to present results for a person who clearly requires more assistance.

C. CASE STUDY: INPATIENT 5

Fig. 6 shows efficiencies in standalone mode, K fixed to 0.5 and adaptable K for inpatient 5, affected by Guillian-

Test number		Jun’09	Jun’09	Jun’09
Control type		Autonomous	Shared PFA	Adaptive K
Global efficiency (%)	Robot	57.07	78.49	76.82
	Human	52.58	68.95	76.73
	Both	55.25	77.65	80.5
Smoothness (%)	Robot	47.11	66.44	62.84
	Human	52.35	69.27	79.38
	Both	51.75	73.26	77.56
Directiveness (%)	Robot	55.1	76.65	73.88
	Human	34.36	41.85	54.91
	Both	43.08	63.75	67.91
Safety (%)	Robot	69.01	92.52	93.7
	Human	70.91	95.63	96.06
	Both	70.91	95.95	96.17
Intervention Level	%	58.82	88.49	90.78
Disagreement	%	10.41	13.63	11.68
	dev	12.29	9.45	9.26
Joystick Variation	%	1.25	2.25	1.74
	dev	5.74	7.98	7.19
Inconsistency	%	5.83	7.33	7.17
Total Length	m	3.47	4.78	5.32
Total Curvature	degrees	272.28	98.72	97.09
Curvature	mean	-0.87	0.22	0.15
	dev	10.87	0.3	0.2
Completion time	sec	18.74	17.48	23.96

TABLE II

IN-PATIENT 5 PROBES DATA

Barrue provoking tetraplegia and also by a strong apraxis (10 over 10). It can be observed that she is not able to complete the path on her own because she finds it very difficult to turn the wheelchair correctly. Shared control with K equal to 0.5 helps her to turn earlier, but since two turns are required in a fairly narrow space, once again she is unable to maneouvre when she gets too close to the armchair. An adaptive K presents two advantages: first, oscillations in the first door are not affecting this inpatient anymore and, since she can drive fairly well in a straight way, she gains control over the wheelchair in most of the trajectory. Second, a better approach to the turn area, plus an increase in assistance, allow her to turn correctly both times now. It is not even necessary to decrease K to 0.25, as the robot approaches the turn from a better position thanks to the inpatient support. Unfortunately, after two turns the person losses directiveness and trajectory needs to be quite corrected at the end, but yet she still manages to gain a K equal to 0.75 for a while. It must be recalled at this point that the robot is not necessarily performing bad when K is high, but rather that the person is doing well, so she does not need so much assistance. In fact, even though inpatient 2 performed pretty well this time, her K was mostly 0.5, meaning that she requires some help most of the time and only gains higher control when the robot performs badly. In most cases, though, persons kept a high K in many trajectory areas, meaning that a fixed K would have provided an unnecessary excess of assistance.

Evaluation of results with all volunteers pointed out that, in fact, they retained control over the wheelchair in any maneouvre they perform well, whereas K went to 0.5 in difficult areas. It rarely went to 0.25 because continuous assistance prevents users from falling into hard control areas, except for persons with mild to severe disabilities. Also, as PFA is used to control the robot and test areas were full of furnitures and fairly narrow, we also checked that the robot contributes less when PFA is not doing well, making it easier for persons to compensate its effects.

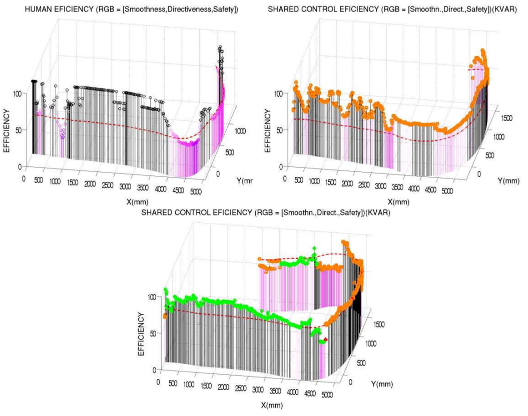

Fig. 6. Efficiencies for standalone, shared control with fixed K and shared control with adaptive envelope.

Fig. 7 presents Intervention Level, Joystick Variation and Disagreement along the path for fixed and adaptive K respectively in these tests. It can be observed that Intervention Level is denser in the second time, meaning that the user is actively cooperating all the time. Furthermore, locations where the person dropped the joystick, marked with red dots in the figure, correspond to decision points in the second case, whereas are more erratic for a fixed K. In both cases, there are less of these points than in standalone mode. This is also coherent with Joystick Variation, which is less noisy and smaller when K is adaptive. This is specially interesting when the inpatient failed to finish the first path, where it can be observed that joystick motion becomes rather erratic in a try to get out of the stuck situation. Finally, although Disagreement is similar in average in both cases, it can be observed that it is lower than the average (discontinous red line) most of the time in the second case, except at the end of the trajectory, where a close turn leads to higher assistance by the robot. When K is fixed, though, Disagreement is usually above the average, meaning that the person does not relate that well with the outcoming action.

To sum up, it can be observed (Tables I and II) that shared control improves efficiencies between 5 and 20% with respect to standalone guidance. Intervention Level is similar or larger in shared mode (93% and 90%) than in standalone mode (99% and 58%). This mean that the user interacts more often with the system and his/her final motion is better in terms of continuity. If we observe only shared modes, there are differences too. In static K mode, disagreement ranges from 2% to 17%, larger than in K variable mode. Efficiency is also smaller (between 2% and 5 %) in fixed K mode than in variable K mode. This seems to point out that the user is more comfortable with adaptable K.

V. CONCLUSIONS AND FUTURE WORKS

This paper has presented a new approach to collaborative control via efficiency based assistance modulation. Collaboration is based on estimating how well user and robot are doing at a given time instant to combine their motion commands in a weighted way, according to a purely reactive control scheme. In order to achieve some inertia

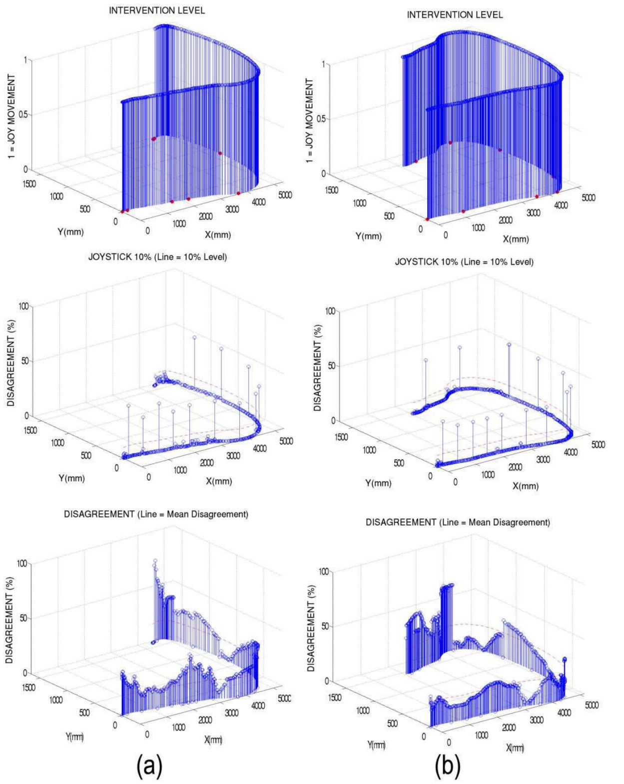

Fig. 7. Intervention Level, Joystick Variation and Disagreement for inpatient 5: a) K fixed (0.5); b) adaptive K

against punctual errors and noise, an envelope is added to increase the contribution of either human or machine on a need basis. This envelope changes according to the temporal average efficiency between the current instant and the last significant discontinuity. The system has been tested in Casa Agevole with volunteering in-patients, presenting physical and sometimes cognitive disabilities. In all cases, collaborative control increased efficiency and all volunteers managed to finish a mildly complex trajectory despite their lack of experience with similar systems. Results prove that the amount of assistance received by users is adapted to their condition and also to the complexity of the maneouvre they are performing, yet they always have a contribution in emerging motion. According to the medical team in the experiments, this is a positive feature to avoid loss of residual abilities and frustration. Future work will focus on adding high level layers to link the proposed system to Activities of Daily Living (ADL).

VI. ACKNOWLEDGMENTS

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