

TABLE IV
RE-IDENTIFICATION PERFORMANCE IN LIVE TESTS IN A CLINIC

FOLLOW							
run	pers.	hyp.	stop-t	stop-f	fp-mm.	pers.-mm.	ref
1	15	748	2	0	3 (2/1)	1	2
2	13	701	3	1	4 (4/0)	0	3
3	14	262	2	1	0	1	1
4	11	772	1	0	0	0	1
5	8	241	1	0	2 (1/1)	0	3
6	6	275	0	0	0	1	0
sum	67	2999	9	2	9 (7/2)	3	10

GUIDE							
run	pers.	hyp.	stop-t	stop-f	fp-mm.	pers.-mm.	ref
1	8	386	1	1	1 (0/1)	0	1
2	13	465	0	2	2 (2/0)	0	1
3	10	847	0	0	0	0	0
4	5	247	0	1	0	0	0
5	12	154	0	0	0	0	1
sum	48	2099	1	4	3 (2/1)	0	3

LEGEND: **pers.**: number of nearby persons while following the user for a distance of 400m along the floor of a rehab clinic. **hyp.**: number of assigned tracking IDs for new person hypotheses (including valid false positive detections). **stop-t**: number of correct stops requested by the re-identification module due to lost user (correct behavior). **stop-f**: number of unnecessary stops requested by the re-identification module (**uncritical**). **fp-mm.**: mismatches of user with false positive person detections (lamps, and the like), in brackets: situation where robot could resolve situation due to user cooperation (**tolerable**) and where it could not (**critical**). **pers.-mm.**: mismatches of user with other persons (**critical**). **ref.**: reference method: mismatches of user with other persons (**critical**).

the user with false positive detections. Manual intervention was necessary three times, when the robot followed false positive detections and could not resolve the situation by itself. This happens if misaligned images showing walls or false detections that were assigned to the track of the user did appear after login in the enrollment phase. Then, the multi-modal template consists of observations of the user and false detections, that may match perfectly to later false detections. Since this happens quiet often, our person detection module should be improved further. Also, a fast visual tracking algorithm [9] can help to validate detections over time.

The robot did very well in stopping when the user was temporally not visible. The few additional stops are acceptable.

At rush-hour times, where the reference approach fails clearly, the visual re-identification performed very well. For example, in the situation shown in Fig. 1, the robot had to follow the proband on a zigzag course through seven people. The user was traced almost through all people, but then he was lost during an evasive maneuver. The robot immediately stopped as desired (highlighted in green in Tab. IV, run 4).

Real-time requirements were always met, and the re-identification module used only 3% of the CPU on average.

V. CONCLUSION

We implemented a person re-identification module that runs on a mobile robot to recognize its user in real-time, using only few amount of the robot's processing resources. It is robust to image blur, varying resolution and illumination, occlusions, and people with walking aids. State-of-the-art performance is confirmed on the standard VIPeR benchmark dataset, as well as on a scenario-specific dataset recorded at a stroke rehab clinic. Additionally, we tested the re-

identification performance live in the addressed operation area during regular day-time routines. During the two hours of following and guiding probands on a track of 4.4 km, the robot came in close contact with 115 other people. Overall, the user was mismatched only three times. Even at rush-hour times, the robot was able to reliably follow and guide probands through the corridor of the clinic. The current performance is acceptable for the upcoming first tests with real patients, when an observer can correct the rare mistakes via a control tablet. For autonomous operation, however, the re-identification performance must be improved further.

Therefore, in our future work, we plan to fuse the proposed visual approach with a non-visual identification, based on a device carried by the patient that can be located by the robot via stereo ultrasound. Additionally, we plan to add more contextual information like predicted walking routes.

REFERENCES

- [1] A. Andrade, A. Pereira, S. Walter, R. Almeida, R. Loureiro *et al.*, "Bridging the gap between robotic technology and health care," *Biomedical Signal Processing and Control*, no. 10, p. 6578, 2014.
- [2] D. S. Cheng, M. Cristani, M. Stoppa, L. Bazzani, and V. Murino, "Custom pictorial structures for re-identification," in *BMVC*, 2011.
- [3] E. Einhorn, T. Langner, R. Stricker, C. Martin, and H.-M. Gross, "Mira - middleware for robotic applications," in *IROS*, 2012, pp. 2591–2598.
- [4] M. Eisenbach, A. Kolarow, K. Schenk, K. Debes, and H.-M. Gross, "View invariant appearance-based person reidentification using fast online feature selection and score level fusion," in *AVSS*, 2012, pp. 184–190.
- [5] M. Eisenbach, A. Kolarow, A. Vorndran, J. Niebling, and H.-M. Gross, "Evaluation of multi feature fusion at score-level for appearance-based person re-identification," in *IJCNN*, 2015.
- [6] M. Farenzena, L. Bazzani, A. Perina, V. Murino, and M. Cristani, "Person re-identification by symmetry-driven accumulation of local features," in *CVPR*, 2010, pp. 2360–2367.
- [7] D. Gray, S. Brennan, and H. Tao, "Evaluating appearance models for recognition, reacquisition, and tracking," in *PETS*, 2007.
- [8] H.-M. Gross, K. Debes, E. Einhorn, S. Mueller, A. Scheidig, C. Weinrich, A. Bley, and C. Martin, "Mobile robotic rehabilitation assistant for walking and orientation training of stroke patients: A report on work in progress," in *SMC*, 2014, pp. 1880–1887.
- [9] A. Kolarow, M. Brauckmann, M. Eisenbach, K. Schenk, E. Einhorn, K. Debes, and H.-M. Gross, "Vision-based hyper-real-time object tracker for human-robot interaction," in *IROS*, 2012.
- [10] A. Kolarow, K. Schenk, M. Eisenbach, M. Brauckmann, H.-M. Gross *et al.*, "Apfel: The intelligent video analysis and surveillance system for assisting human operators," in *AVSS*, 2013, pp. 195–201.
- [11] B. Ma, Y. Su, and F. Jurie, "Bicov: a novel image representation for person re-identification and face verification," in *BMVC*, 2012.
- [12] B. Ma, Y. Su, and F. Jurie, "Local descriptors encoded by fisher vectors for person re-identification," in *ECCV*, 2012, pp. 413–422.
- [13] T. Ojala, M. Pietikäinen, and T. Mäenpää, "Multiresolution gray-scale and rotation invariant texture classification with local binary patterns," *TPAMI*, vol. 24, pp. 971–987, 2002.
- [14] B. Prosser, W. Zheng, S. Gong, and T. Xiang, "Person re-identification by support vector ranking," in *BMVC*, 2010.
- [15] M. Volkhardt, C. Weinrich, and H.-M. Gross, "People tracking on a mobile companion robot," in *SMC*, 2013, pp. 4354–4359.
- [16] C. Weinrich, C. Vollmer, and H.-M. Gross, "Estimation of human upper body orientation for mobile robotics using an svm decision tree on monocular images," in *IROS*, 2012, pp. 2147–2152.
- [17] C. Weinrich, T. Wengelfeld, C. Schroeter, and H.-M. Gross, "Generic distance-invariant features for detection of people with walking aid in 2d range data," in *RO-MAN*, 2014, pp. 767–773.
- [18] F. Xiong, M. Gou, O. Camps *et al.*, "Person re-identification using kernel-based metric learning methods," in *ECCV*, 2014, pp. 1–16.
- [19] R. Zhao, W. Ouyang, and X. Wang, "Unsupervised salience learning for person re-identification," in *CVPR*, 2013, pp. 3586–3593.
- [20] W. Zheng, S. Gong *et al.*, "Person re-identification by probabilistic relative distance comparison," in *CVPR*, 2011, pp. 649–656.