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# Human-Aware Navigation for Autonomous Mobile Robots for Intra-factory Logistics

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**Abstract.** This paper presents a human-aware navigation system for mobile robots targeted to cooperative assembly in intra-factory logistics scenarios. To improve overall efficiency of the operator-robot ensemble, assembly stations and operators are modelled as cost functions in a layered cost map supporting the robot navigation system. At each new sensory update, the system uses each operator's estimated location to affect the cost map accordingly. To promote predictability and comfort in the human operator, the cost map is affected according to the Proxemics theory, properly adapted to take into account the layout activity space of the station in which the operator is working. Knowledge regarding which task and station are being handled by the operator are assumed to be given to the robot by the factory's computational infrastructure. To foster integration in existing robots, the system is implemented on top of the navigation system of the Robot Operating System (ROS).

**Keywords:** Navigation, Human-Aware, Autonomous Navigation, Manufacturing Systems, Intra-factory Logistics

## 1 Introduction

Nowadays, robotics is ubiquitous on almost all industries. However, given the ever increasing need for diversification and customization of products and services, a new wave of flexible and more collaborative robots are being introduced into the shop floor. The goal is to have fenceless environments where robots and operators can collaborate to increase the efficiency of assembly tasks.

Robots in manufacturing are expanding from more traditional operations, as welding and painting, to factory intra-logistics [9] and collaborative assembly [11]. These new tasks demand for a shift in the human-robot interaction paradigm in manufacturing, where robots need to adapt to their humans counterparts and not the other way around. Although more and more autonomous mobile robots are specifically designed for shop floors [1, 6, 14], their navigation systems are still not fully tuned for this new approach.

Despite the fact that human-awareness in robot navigation tasks has been considerably studied for office environments, museums, and households [7], in the manufacturing domain human-awareness has been mostly limited to manipulation tasks [12]. Manufacturing processes are often designed to be not only safe but as efficient as possible, leaving human comfort as a secondary goal. This is

aggravated by the non-optimal behaviour often observed in humans when complying with social conventions [4]. For these reasons concepts like operator comfort, naturalness of motion, and sociability are often disregarded in shop-floor design.

Comfort in human-to-human interactions can be severely influenced by distance, with the necessary personal space dependent on the relationship, intention, and culture, as predicted by the theory of proxemics [5]. Transferring this human-human proxemics to human-robot proxemics is one way of improving navigation systems [13]. Inspired by the proxemics theory, human comfort can be increased by defining areas around humans with appropriate cost functions or potential fields [3, 10]. This approach allows robots to operate in close proximity to humans even in confined spaces, which is especially relevant in shop floors where the very high square footage cost promotes a high occupancy rate.

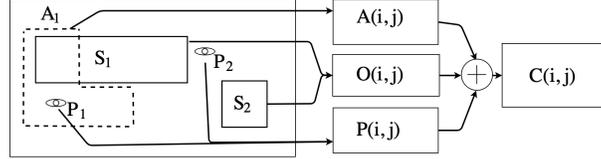
Respecting personal zones is only part of the problem as objects also interfere with human comfort and interaction. For instance, if a given screen is being attended by a person, the space between both must be free of obstacles, even if the obstacles do not violate the person’s personal space [2]. However, if no one is attending to the screen, then the *affordance space* does not constitute an *activity space* [8] and, so, the presence of occluding obstacles causes no problems. In manufacturing, shelves in warehouses and assembly stations need to be always accessible to operators and, hence, there is an operational cost associated to having robots traversing that space that should be translated into the mobile robot’s navigation cost map. To account for both spatial affordances of assembly stations and personal spaces of operators, the proposed system relies on layered cost maps [10].

This paper proposes that operators found by the robot while traversing the environment should induce the overlay of a cost function on the layered cost map according to the proxemics theory, thus ensuring that the mobile robot does not violate the operators’ personal space. In the proposed system, assembly stations without assigned operators are simply represented as an obstacle in the layered cost map. The extent of the station’s influence in the cost map is expanded, according to a conservative application of the proxemics theory, when an operator is known to be present therein. This way the mobile robot tends to avoid more strongly the station if the latter is assigned to an operator. Location, layout, task, and operator assignments of stations are assumed to be available to the robot via the factory’s manufacturing enterprise systems (MES).

## 2 Proposed Human-Aware System

The fundamental aspect of this work is the application of the proxemics theory to the specificity of collaborative assembly scenarios and the use of a multiple layered costmap for its implementation (see Fig. 1). The costmap integrates three 2D layers, the first representing cost induced by the activity spaces of each station,  $A(i, j)$ , the second the cost reflected by the obstacles detected by range sensors,  $O(i, j)$ , and the third the cost resulting from the presence of the

operators according to the proxemics theory,  $P(i, j)$ , where  $(i, j)$  is the index of each cell of the gridmap. The three layers are combined into a single cost map,  $C(i, j)$ , with a simple weighted average (as detailed below).



**Fig. 1.** Systems layered cost map overview. The polygons with solid line and labelled  $S_1$  and  $S_2$  depict assembly stations while the polygon with the dotted line that is labelled  $A_1$  depicts an activity space. Operators are represented by the objects with  $P_1$  and  $P_2$  labels.  $A(i, j)$ ,  $O(i, j)$ ,  $P(i, j)$  are depictions of the costmap layers of activity spaces, obstacles, and operator presence, respectively.  $C(i, j)$  is the fusion of all three layers, obtained with a simple weighted average.

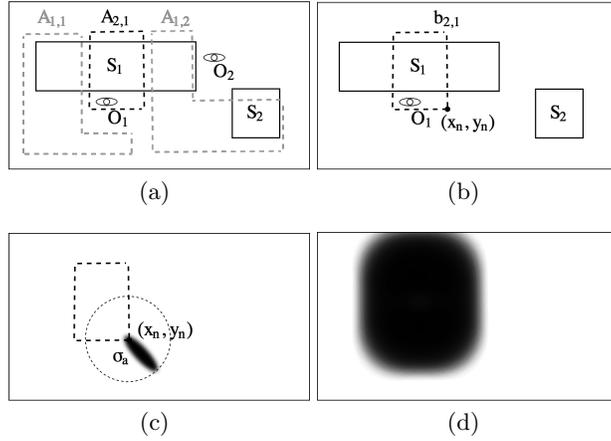
The proposed navigation system adapts to the human presence and to the assembly environment with two simultaneous methods. The first method detects the operators inside the robot’s sensors’ field-of-view and associates to each of them a cost function based on the proxemics theory in a similar approach to the one proposed in [10]. Concretely, the layer contains each detected operator associated cost:

$$P(i, j) = \max\{P_1(i, j), \dots, P_n(i, j)\}, \quad (1)$$

$$P_k(i, j) = \mathcal{N}_{x_k, y_k, \theta_k, \sigma_k}(i, j), \quad (2)$$

where  $n$  is the number of operators currently detected, and  $P_k(i, j)$  represents the Gaussian-shaped cost induced by the personal space of operator  $k$ , and  $(x_k, y_k, \theta_k)$  define the 2D pose of the operator and  $\sigma_k$  distribution’s variance based on the personal space definition of the proxemics theory.

The second method maps the concept of *activity space* to every station of the shop-floor. Each activity space is spatially represented by its boundaries as a convex polygon. While each station can have multiple activity spaces, only one is considered at any given moment. Concretely, an activity space is only considered to the costmap if it is associated with current task’s stage and if an operator has been detected inside its boundary (see Fig. 2(a)). The boundaries of the station’s activity spaces are extracted from the manufacturing enterprise system (MES) (see Fig. 2(b)). Each station  $s$  has at least one activity space  $a$  associated with its boundary, defined by  $b_{a,s} = \{(x_1, y_1), \dots, (x_n, y_n)\}$ , where  $n$  is the number of points of the boundary’s convex polygon. In the proxemics theory, personal space is represented as an directional anisotropic ellipse with the larger axis aligned with forward movement. However, the uncertainty associated with both the operator’s detection and her/his next possible motion when in an assembly station needs to be addressed. To do so the directional anisotropic



**Fig. 2.** Diagrams representing the work-flow of the creation of the multi-layered costmap activity layer. The polygons with solid line and labelled  $S_1$  and  $S_2$  depict assembly stations while the polygons with the dotted lines define activity spaces. (a) Activity space 2 of station 1 ( $A_{2,1}$ ) activated by presence of operator  $O_1$ . (b) Convex polygon defined by boundary  $b_{2,1}$  where each point  $(x_n, y_n)$  is iterated to create the final cost function. (c) To take into account the uncertainty of the operators next position the ellipse of proxemic space is rotated 360 degrees around each  $(x_n, y_n)$  point. (d) The final cost map of activity  $A_{2,1}$ .

ellipse associated with personal space is fully rotated around each point of the activity space's boundary (see Fig. 2(c)). The full revolution of the anisotropic ellipse is approximated by superposing a Gaussian function centred on each of the boundary points associated to a given activity space  $a$  of station  $s$  (see Fig. 2(c)):

$$A_{a,s}(i, j) = \max\{\{\mathcal{N}_{x_m, y_m, \sigma_a}(i, j) : \forall (x_m, y_m) \in b_{a,s}\}, \quad (3)$$

where  $(x_m, y_m)$  represents a point along boundary  $b_{a,s}$ . Given that the robot's own tasks may require the navigation goal to be inside an activity space, represented by  $a_c$ , in that case it is not accounted for the activity layer:

$$A(i, j) = \max\{A_{a,s} : \forall a \in L_s \setminus \{a_c\}, s \in S\} \quad (4)$$

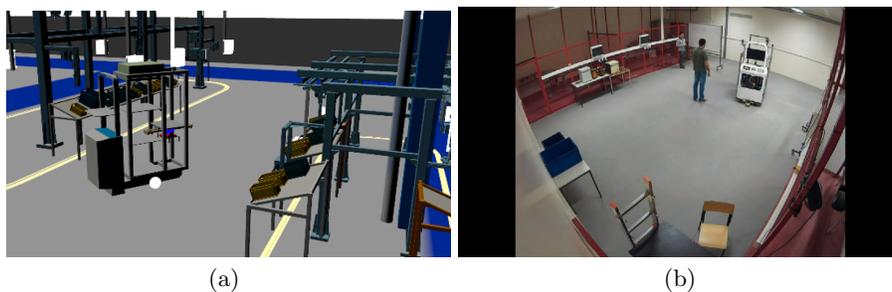
where  $L_s$  is the set of activity spaces for a given station  $s$  and  $S$  is the set of stations in the shopfloor. Both methods result in independent costmap layers that are fused with a layer with the obstacles detected by the robot's sensors and the map of the environment obtained via MES:

$$C(i, j) = \omega_o O(i, j) + \omega_p P(i, j) + \omega_a A(i, j), \quad (5)$$

where  $\omega_o$ ,  $\omega_p$ , and  $\omega_a$  are empirically defined weights associated with the obstacle layer, proxemics layer, and activity layers, respectively. The resulting costmap is then used to modulate the robot's navigation system behaviour.

### 3 Preliminary Experimental Results

The proposed human-aware navigation system is being developed and tested both in simulation and in a real environment (see Fig. 3). The experimental setups created include multiple assembly stations, warehouses, and obstacles normally present in a shopfloor. Operators are also present performing real or simulated assembly tasks during the robot’s operation. The robot model used in the experiments is the Intralogistics Mobile Assistant Unit (IMAU) developed for the intralogistics tasks in automotive shopfloor environments (for more detail refer to [9]). During these preliminary runs the system showed the ability to modulate navigation behaviour based on the detection of the operators and activity spaces (see Fig. 3).



**Fig. 3.** Snapshots of the preliminary experimental runs. (a) The simulation environment developed to mimic a automotive shopfloor. (b) The human operator being detected by the robot’s onboard sensors during a preliminary run.

### 4 Conclusions and Future Work

An human-aware navigation system for autonomous mobile robots capable of performing intralogistics tasks in assembly shopfloors was presented. A set of preliminary experiments in both simulation and lab environment showed the potential of the proposed system to affect the navigation of the mobile robot to increase operator comfort. Based on a multi-layered costmap the proposed system models both activity spaces and operators in different layers and fuses them with obstacle information. Exploiting offline information of task type, topology, and online detection of operators, the system reduces the number of violations of the operators personal space. In the future we expect to validate the system in a larger variety of environments and applications inside the manufacturing scope. Finally, we also intend to improve the system by learning operator’s behaviour in each specific task introducing this information into a novel estimator. We also aim to improve the cost representation of the different stations and tasks by gath-

ering information from all sensors present in the shopfloor, reducing temporal uncertainty related to each operator's location.

## References

1. Bøgh, S., Schou, C., Rühr, T., Kogan, Y., Dömel, A., Brucker, M., Eberst, C., Tornese, R., Sprunk, C., Tipaldi, G.D., et al.: Integration and assessment of multiple mobile manipulators in a real-world industrial production facility. In: *ISR/Robotik 2014; Proceedings of 41st Intl. Symposium on Robotics*. pp. 1–8. VDE (2014)
2. Bransford, J., Shaw, R.E.: *Perceiving, acting, and knowing: toward an ecological psychology*. Lawrence Erlbaum Associates distributed by the Halsted Press division of John Wiley and sons (1977)
3. Chik, S.F., Yeong, C.F., Su, E.L.M., Lim, T.Y., Duan, F., Tan, J.T.C., Tan, P.H., Chin, P.J.H.: Gaussian pedestrian proxemics model with social force for service robot navigation in dynamic environment. In: *Asian Simulation Conference*. pp. 61–73. Springer (2017)
4. Chung, S.Y., Huang, H.P.: Incremental learning of human social behaviors with feature-based spatial effects. In: *International Conference on Intelligent Robots and Systems (IROS)*. pp. 2417–2422. IEEE (2012)
5. Hall, E.: *The Hidden Dimension : man's use of space in public and in private* (1969)
6. Hvilshøj, M., Bøgh, S.: little helper an autonomous industrial mobile manipulator concept. *International Journal of Advanced Robotic Systems* 8(2), 15 (2011)
7. Kruse, T., Pandey, A.K., Alami, R., Kirsch, A.: Human-aware robot navigation: A survey. *Robotics and Autonomous Systems* 61(12), 1726–1743 (2013)
8. Lindner, F., Eschenbach, C.: Towards a formalization of social spaces for socially aware robots. *Spatial Information Theory* pp. 283–303 (2011)
9. Lourenço, A., Marques, F., Mendonça, R., Pinto, E., Barata, J.: On the design of the robo-partner intra-factory logistics autonomous robot. In: *2016 IEEE Intl. Conf. on Systems, Man, and Cybernetics (SMC)*. pp. 2647–2652. IEEE (2016)
10. Lu, D.V., Hershberger, D., Smart, W.D.: Layered costmaps for context-sensitive navigation. In: *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2014)*. pp. 709–715. IEEE (2014)
11. Matthias, B., Kock, S., Jerregard, H., Källman, M., Lundberg, I.: Safety of collaborative industrial robots: Certification possibilities for a collaborative assembly robot concept. In: *IEEE International Symposium on Assembly and Manufacturing (ISAM), 2011*. pp. 1–6. IEEE (2011)
12. Michalos, G., Makris, S., Tsarouchi, P., Guasch, T., Kontovrakis, D., Chryssolouris, G.: Design considerations for safe human-robot collaborative workplaces. *Procedia CIRP* 37, 248–253 (2015)
13. Rios-Martinez, J., Spalanzani, A., Laugier, C.: From proxemics theory to socially-aware navigation: A survey. *International Journal of Social Robotics* 7(2), 137–153 (2015)
14. Sprunk, C., Lau, B., Pfaff, P., Burgard, W.: An accurate and efficient navigation system for omnidirectional robots in industrial environments. *Autonomous Robots* 41(2), 473–493 (2017)