# How A Navigating Robot Decides Whether To Exploit Human Cooperation: Potential Co-Cost Minimization Principle

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***Abstract*—Human aware robot navigation, which takes human factors into account, has been researched more and more for mobile robotics. Navigating in a human existing environment, a robot had better neither neglect potential human cooperation nor always exploit human cooperation. In this paper, we propose the *potential co-cost minimization principle* (PCCMP) and the generic PCCMP architecture in the context of human aware robot navigation. We describe a concrete instantiation of the PCCMP and demonstrate with simulation results how the PCCMP architecture enables a robot to flexibly and reasonably decide whether to exploit human cooperation according to concrete scenario conditions.**

## I. Introduction

Mobile robots have successfully found its way in many useful applications, such as the automated guided vehicle (AGV) operating in industrial environments. Daily-life scenarios have become more and more important stages for mobile robots. For example, a mobile robot can serve as a guide in a museum [1] and an exhibition [2], deliver services in an office [3], and assist routine works in a hospital [4]. In daily-life scenarios, humans are likely to exist and the robot had better not neglect their existence during its navigation.

Early attempts on robot navigation often followed obstacle-avoidance-oriented methodology (such as purely reactive navigation [5] [6]) and did not pay special attention to existing humans in an environment. In other words, early mobile robots did not distinguish between humans and other environment objects during their navigation. Since a decade ago, researchers have been making efforts on embodying robots with certain social intelligence in addition to purely machinery ability, with a goal of reducing social discomforts aroused by robots and making robots more socially acceptable [7] [8]. In order to achieve this, the robot has to be aware of humans in the environment. The authors in [9] proposed the framework of "human aware motion planner" (HAMP) which provides a general strategy of how to take human factors into account in the robot navigation. A similar general framework has been proposed in [10].

Following the HAMP strategy, the problem of motion planning goes to the problem of establishing cost models for human-related criteria besides robot-related criteria in the robot navigation and the problem of optimizing a cost (objective) function based on the established cost models. For example, besides the cost model of a human centred Gaussian circle as originally used in [9], the cost model of a heuristically adaptive ellipse [11] or that obtained from off-line learning [12] may better characterize the personal space of a moving human. The A* search with a variable grid, which is more efficient than the classical A* search with a constant grid, has been adopted to search for the optimal path dynamically in real time [10]. One can refer to a recent report [13] for an extensive state-of-the-art on human aware robot navigation and related topics.

Existing research works on human aware robot navigation rarely exploit potential human cooperation. However, neglecting potential human cooperation may incur much navigation cost to a robot. Consider the scenario shown in Fig.1 as an example. In this scenario, a robot (marked by the red solid circle) is currently at the START point and plans to go from the START point to the GOAL point. There are two parts of navigable space linking the START point and the GOAL point, i.e. the left passage and the right passage. The left passage is currently blocked by a human (marked by the yellow solid circle).

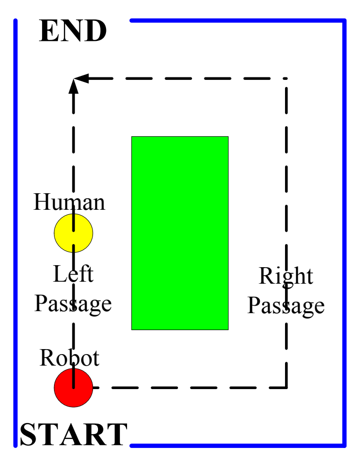


Fig. 1. A scenario with two passages: the left one short but blocked by a human; the right one free but long

Without exploiting human cooperation, the robot has no choice but putting up with the right passage that incurs more travelling distance. However, the human has the potential to move aside to let the robot pass by. The robot may exploit this potential human cooperation and benefit from the short passage on the left. On the other hand, always exploiting human cooperation [14] [15] is also undesirable, because sometimes it is inconvenient or even infeasible for the human to cooperate with the robot in an intended way.

As in above scenario, when the robot is currently at the START point and *has to* take a choice between following the left passage hence exploiting potential human cooperation and following the right passage without exploiting human cooperation, a problem arises naturally for the robot: how does it *reasonably* decide whether to exploit human cooperation?

By so far as we know, no reported research work explicitly handles this problem. In this paper, we propose a principle, coined as *potential co-cost minimization principle*, which serves as a solution to this problem. This paper is organized as follows: in section II, the potential co-cost minimization principle is put forward, based on a sociological reflection. In section III, a concrete instantiation of putting this principle into practice is described. Simulation demonstration is given in section IV, followed by a conclusion in section V.

## II. A Sociological Reflection and the Potential Co-Cost Minimization Principle

### A. Assumptions on reasonableness and equality

Before continuing, it is worth specifying two basic assumptions of the presented works: reasonableness and equality.

*1) Reasonableness assumption:* A profound discussion on the concept *reasonable* may be complicated and is out of the focus of this paper. Here, we simply adopt the idea of *instrumental reasonableness* (or *rationality*) from the sociology domain [16] [17], i.e. a process is regarded as reasonable for an individual if it can enhance certain *utility* or reduce certain *cost* for the individual. For example, the daily-life behaviour of following a straight line to go from a point to another point can be regarded as reasonable because it can reduce the distance (a sort of cost) that we have to traverse, or in other words, it can enhance the efficiency (a sort of utility) of our movement.

In the context of robot navigation, instrumental reasonableness has already been often followed. A typical example is the robot motion planner that searches for the shortest path to fulfil a navigation task. If the travelling distance is treated as the cost borne by the robot, the reasonableness of this kind of motion planner consists in that it generates cost-effective movements for the robot. Besides cost borne by robots, cost borne by humans has also been taken into account in robot motion planners, which is the basic idea of human aware robot navigation [9] [10] [11] [12] [13]. The cost, no matter borne by robots or by humans, can be modelled in various ways in reality. In this section, however, we temporarily neglect concrete instantiation of the cost and would rather refer to the term cost in a generic way.

*2) Equality assumption:* We briefly explain the equality between humans and robots in certain sense. We have no intention to carry out ethical discussions on long-term human-robot relationship as in [18]; we simply admit that a robot is by no means strictly comparable to a human. On the other hand, one had better note that robots are designed to serve humans and they are unlikely to move idly in an environment without any human-serving purpose—For cases where they do have no specific tasks, they are usually programmed to stay stationary out of safety and economy consideration—Since a robot normally operates on behalf of certain humans (named *clients*), the more efficiently can it finish a required task, the more utility or the less cost can it bring to its client(s).

For example, still consider the scenario shown in Fig.1, the robot may choose the right passage, in order not to disturb the encountered human in the left passage. However, imagine that the robot is leading a guest, then its choice of the detour will incur more walking cost to the guided guest. Or imagine that the robot is going to deliver a service to a client, then its choice will incur more waiting cost to the client. As shown in this example, the robot had better care its own convenience as well as that for the encountered human, in order that the cost borne by its client and the encountered human can be balanced.

Therefore, for the robot, it is indeed the equality between the humans encountered and the clients served or intended to be served that is cared here. In other words, the robot can be somewhat treated as a representative for its clients.

Besides, even only consider the relationship between the robot itself and the human, the equality assumption is not a totally unrealistic imagination; in fact, as observed by a number of researchers [8] [15] [10], a human does have tendency to treat a robot also as a human. There may be certain cultural reasons for this: the vulgarisation of the concept "robot", be it through schools or media etc, has well popularized the idea that a robot possesses (or is intended to possess) certain "intelligence" normally exclusive to a human.

### B. Reciprocal altruism

In the scenario shown in Fig.1, if the robot chooses to follow the right passage without exploiting human cooperation, then the cost borne by the human is naturally zero; let the optimal non-cooperative navigation process be denoted as $\mathbf{N_{opt}}$ and let the minimum cost borne by the robot under $\mathbf{N_{opt}}$ be denoted as $c_R(\mathbf{N_{opt}})$.

Consider the case where the robot chooses to follow the left passage hence exploiting potential human cooperation; given a potential cooperative navigation process (denoted generically as $\mathbf{C}$) i.e. a robot navigation process that needs certain potential human cooperation, let the cost borne by the robot and the human under $\mathbf{C}$ be denoted as $c_R(\mathbf{C})$ and $c_H(\mathbf{C})$ respectively.

We examine the following problem: *given a specific* $\mathbf{C}$*, how to judge whether* $\mathbf{C}$ *is reasonable with respect to* $\mathbf{N_{opt}}$? Here, "reasonable" concerns both the robot and the human, according to the equality assumption; i.e. reasonable for the robot as well as for the human.

One may notice that any $\mathbf{C}$, if examined isolatedly, will never be reasonable because it will always incur certain cooperation cost to the human whereas this cost is zero under $\mathbf{N_{opt}}$. However, a type of process rarely happens uniquely in the long run and may happen reciprocally among individuals from time to time. Thus, instead of examining the cost borne by each individual in a single process, we borrow the theory of *reciprocal altruism* [17] [19] from the sociology domain and examine the cost borne by each individual in a statistical way.

For the scenario shown in Fig.1, the reciprocal altruism can be explained as follows: imagine that in another occasion, the robot and the human exchange their position, i.e. the human plans to go from the START point to the GOAL point whereas the robot blocks the left passage.

Consider the two occasions together: under $\mathbf{C}$ in the current occasion, the robot bears a cost of $c_R(\mathbf{C})$ whereas the human bears a cost of $c_H(\mathbf{C})$ as the cooperation cost. In the other occasion, the robot reciprocates the cooperation and bears a cost of $c_H(\mathbf{C})$, whereas the human bears a cost of $c_R(\mathbf{C})$. Each of the human and the robot bears a cost of $[c_R(\mathbf{C})+c_H(\mathbf{C})]/2$ on average.

On the other hand, if there is **n**o cooperation, the robot and the human bear a cost of $c_R(\mathbf{N_{opt}})$ and zero cost respectively in the current occasion. Their status are exchanged in the other occasion, where the robot bears zero cost and the human bears a cost of $c_R(\mathbf{N_{opt}})$. Each of the human and the robot bears a cost of $c_R(\mathbf{N_{opt}})/2$ on average. Then, $\mathbf{C}$ is regarded as reasonable from each individual's perspective if

$$[c_R(\mathbf{C}) + c_H(\mathbf{C})]/2 < c_R(\mathbf{N_{opt}})/2 \text{ i.e.}$$
$$c_R(\mathbf{C}) + c_H(\mathbf{C}) < c_R(\mathbf{N_{opt}})$$

According to the reciprocal altruism, individuals do not focus on the cost in an isolated process. They may sacrifice their benefits somewhat in favour of more benefits of others because they believe that others will reciprocate in a similar situation. As a result, each individual can benefit from the reciprocal altruism in a statistical sense.

Despite the existence of opportunists (reluctant to make any sacrifice in any occasion) in the society, we believe that the major part of individuals are likely to cooperate with others and follow the spirit of the reciprocal altruism in daily-life.

### C. Potential co-cost minimization principle (PCCMP)

Following above analysis, we put forward the *potential co-cost minimization principle* (PCCMP):

**PCCMP**: if there exists $\mathbf{C}$ satisfying $c_R(\mathbf{C}) + c_H(\mathbf{C}) < c_R(\mathbf{N_{opt}})$, the attempt of the robot to exploit human cooperation is regarded as reasonable. If such $\mathbf{C}$ does not exist, this attempt is regarded as unreasonable.

In other words, whether the attempt of the robot to exploit human cooperation is regarded as reasonable depends on whether potential cooperation helps reducing the co-cost borne by the robot and the human. If the cooperation, no matter carried out in which way, can not reduce the co-cost, then the robot had better refrain from exploiting human cooperation.

Let $\mathbf{C}_{opt}$ denote the optimal potential cooperative navigation process:

$$\mathbf{C}_{opt} = \arg\min_{\mathbf{C}}\{c_R(\mathbf{C}) + c_H(\mathbf{C})\}$$

If there exists $\mathbf{C}$ satisfying $c_R(\mathbf{C})+c_H(\mathbf{C}) < c_R(\mathbf{N_{opt}})$, then

$$c_R(\mathbf{C}_{opt}) + c_H(\mathbf{C}_{opt}) \leq c_R(\mathbf{C}) + c_H(\mathbf{C}) < c_R(\mathbf{N_{opt}})$$

If $c_R(\mathbf{C}_{opt}) + c_H(\mathbf{C}_{opt}) \geq c_R(\mathbf{N_{opt}})$, then $\forall\mathbf{C}$ we have

$$c_R(\mathbf{C}) + c_H(\mathbf{C}) \geq c_R(\mathbf{C}_{opt}) + c_H(\mathbf{C}_{opt}) \geq c_R(\mathbf{N_{opt}})$$

Thus the PCCMP can also be stated as follows:

**PCCMP**: If $c_R(\mathbf{C}_{opt}) + c_H(\mathbf{C}_{opt}) < c_R(\mathbf{N_{opt}})$, then the attempt of the robot to exploit human cooperation is regarded as reasonable; otherwise, regarded as unreasonable.

As the cost borne by the human in the non-cooperative case is zero, $c_R(\mathbf{N_{opt}})$ can be treated as the co-cost borne by the robot and the human, i.e. $c_R(\mathbf{N_{opt}})+0$. This is why in PCCMP we use the term *co-cost* uniformly without distinguishing between the cooperative case and the non-cooperative case.

### D. Discussion

It is worth noting the novelty of the PCCMP with respect to existing idea of *co-cost minimization* in related works such as presented in [9] [10]. In existing works, humans are usually treated as if they never react to the robot; potential cooperation of the humans towards the robot, which may affect the co-cost, is not considered. In contrast, in the PCCMP, *potential* human cooperation and its effect on the co-cost are taken into account; in other words, it is the *potential co-cost* that is evaluated.

## III. PCCMP Architecture: An Instantiation of Cost Modelling and Optimization Solving

We put forward the *PCCMP architecture* for the robot to decide whether to exploit human cooperation. We describe a concrete instantiation of this architecture for the dyadic scenario (a robot and a human) as shown in Fig.1, which serves as an example to demonstrate the function of this architecture.

### A. Generic PCCMP architecture

- Step 1 Find the **n**on-cooperative navigation process $\mathbf{N}_{opt}$ that minimizes the cost borne by the robot; denote the optimal cost as $c_R(\mathbf{N}_{opt})$.
- Step 2 Find the potential **c**ooperative navigation process $\mathbf{C}_{opt}$ that minimizes the co-cost borne by the robot and the human; denote the optimal co-cost as $c_R(\mathbf{C}_{opt}) + c_H(\mathbf{C}_{opt})$
- Step 3 Compare $c_R(\mathbf{C}_{opt}) + c_H(\mathbf{C}_{opt})$ with $c_R(\mathbf{N}_{opt})$ and judge whether the attempt to exploit human cooperation is reasonable or not according to the PCCMP. If reasonable, the robot may exploit human cooperation; otherwise, not.

### B. Instantiation: Cost modeling

We describe a concrete instantiation of the PCCMP architecture by specifying the cost modelling and the optimization solving in this and next sub-sections respectively; we consider two kinds of cost: *motion cost* and *safety cost*.

*1) Motion cost:* For the robot, the motion cost here means the distance to move to arrive at the GOAL point. Denote a generic navigation path and its length as $\mathbf{P}$ and $c_{RM}(\mathbf{P})$ respectively.

For the human, the motion cost means the distance that she/he has to move to make the robot be able to pass by. Denote the default position of the human as $\mathbf{H}_D$, denote as $\mathbf{H}$ generically a potential position that the human may stay temporarily to make the way for the robot. The motion cost borne by the human, denoted as $c_{HM}(\mathbf{H})$, is computed as:

$$c_{HM}(\mathbf{H}) = 2\|\mathbf{H} - \mathbf{H}_D\| \tag{1}$$

$c_{HM}(\mathbf{H})$ includes not only the motion cost borne by the human to move from $\mathbf{H}_D$ to $\mathbf{H}$ but also that borne by she/he to move back to $\mathbf{H}_D$. This is why there is a factor of "2" in (1).

*2) Safety cost:* For both the human and the robot, the safety cost here means the cost to bear in the proximity of an object.

The safety cost borne by humans has been commonly considered in existing research works on human aware robot navigation [9] [10] [11] [20]. In these research works, the safety cost is usually treated as a kind of psychological discomfort aroused by close objects, which is based on the proxemics theory [21] from the sociology domain. Instead, we simply treat the safety cost as a kind of purely physical risk of colliding with a close object. In this sense, the safety cost also concerns the robot that does not have human-like psychology.

For the human or the robot, denote the distance of an object as $d$; denote the safety cost caused by this object as $c_S(d)$, which is modelled as:

$$c_S(d) = \begin{cases} 0 & \text{if } d \geq b \\ a(\frac{1}{d} - \frac{1}{b}) & \text{if } d > 0 \\ \infty & \text{if } d \leq 0 \end{cases} \qquad (2)$$

An interpretation of the model: $d$ being equal or below zero indicates a collision with the object, which should be absolutely avoided and hence infinite safety cost is imposed. The safety cost, which reflects the potential risk of colliding with the object when the object distance is beyond zero, decreases as the object distance increases. Beyond certain distance threshold $b$, the safety cost or collision risk may be neglected.

We may set the model coefficients $a$ and $b$ in (2) differently for the human and for the robot. Let the coefficients set for the human and the robot be denoted as $\{a_H, b_H\}$ and $\{a_R, b_R\}$ respectively and let corresponding safety cost functions be denoted as $c_{HS}(d)$ and $c_{RS}(d)$ respectively

*3) Cost objective function in step 1:* In step 1 of the PCCMP architecture, the robot searches for the optimal non-cooperative navigation process in the right passage (see Fig.1)—a navigation process can be characterized by the navigation path $\mathbf{P}$; denote the optimal navigation path as $\mathbf{P}_{opt}$—$\mathbf{P}$ has infinite dimension and a strictly optimal solution may be difficult to find. We instead tries to find a semi-optimal solution of $\mathbf{P}$ which is approximated by finite *milestone points* and a group of line segments that connect the START point, the milestone points, and the GOAL point consecutively. Here, we use two milestone points situated at the two corner areas in the right passage; see Fig.2. Denote the two milestone points as $\mathbf{P}_m = \{\mathbf{P}_{m1}, \mathbf{P}_{m2}\}$.

Instead of considering the safety cost associated with the infinite points on $\mathbf{P}$, we consider the safety cost only associated with the milestone points. The motion cost is the sum of length of the line segments of $\mathbf{P}$. Therefore, the cost borne by the robot is computed as:

$$\begin{aligned} c_{R1}(\mathbf{P}_m) = \|\mathbf{P}_{start} - \mathbf{P}_{m1}\| + \|\mathbf{P}_{m1} - \mathbf{P}_{m2}\| \\ + \|\mathbf{P}_{m2} - \mathbf{P}_{end}\| + \sum_{i=1}^{3} c_{RS}(d_{1i} - s_R) \\ + \sum_{i=1}^{3} c_{RS}(d_{2i} - s_R) \end{aligned} \qquad (3)$$

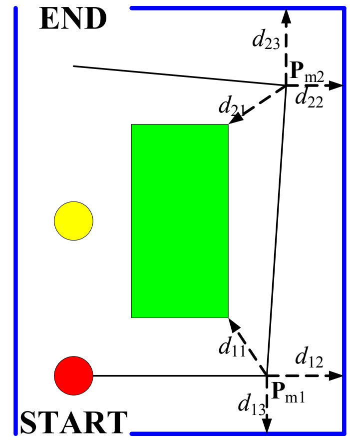


Fig. 2. Non-cooperative navigation process in the right passage: milestone points based representation

$d_{ij}$ ($i$=1-2; $j$=1-3) denotes the distances of the milestone points to environment infrastructure; see Fig.2. $s_R$ denotes the radius of the robot (the robot and the human are modelled as circles).

*4) Cost objective function in step 2:* In step 2 of the PCCMP architecture, the robot searches for the optimal potential cooperative navigation process in the left passage that minimizes the co-cost borne by the robot and the human. Here, a potential cooperative navigation process is characterized by the human's potential position $\mathbf{H}$ (see section III-B1) and a milestone point $\mathbf{P}_{m3}$ on the robot's path. Without loss of generality, suppose the left passage is vertical, $\mathbf{P}_{m3}$ is chosen to be on the same level with $\mathbf{H}$; in other words, $\mathbf{P}_{m3}$ represents the place where the robot passes by the human. See Fig.3.

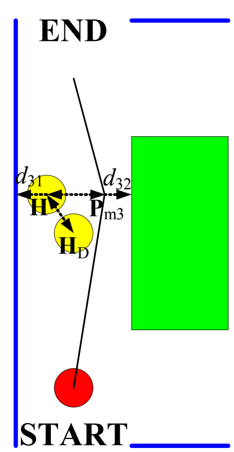


Fig. 3. Potential cooperative navigation process in the left passage

$d_{31}$ and $d_{32}$ respectively denote the distance of $\mathbf{H}$ and $\mathbf{P}_{m3}$ to environment infrastructure. As in step 1, we consider the safety cost only associated with the milestone points. The cost borne by the robot is computed as:

$$\begin{aligned} c_{R2}(\mathbf{P}_{m3}, \mathbf{H}) = \|\mathbf{P}_{start} - \mathbf{P}_{m3}\| + \|\mathbf{P}_{m3} - \mathbf{P}_{end}\| \\ + c_{RS}(d_{32} - s_R) + c_{RS}(\|\mathbf{H} - \mathbf{P}_{m3}\| - s_R - s_H) \end{aligned} \qquad (4)$$

$s_H$ denotes the radius of the human. The cost borne by the human is computed as:

$$c_H(\mathbf{P}_{m3}, \mathbf{H}) = c_{HM}(\mathbf{H}) + c_{HS}(d_{31} - s_H) + c_{HS}(\|\mathbf{H} - \mathbf{P}_{m3}\| - s_R - s_H) \quad (5)$$

### *C. Instantiation: Optimization solving*

In step 1, solve the following optimization problem:

$$\mathbf{P}_{m,opt} = \arg\min_{\mathbf{P}_m}\{c_{R1}(\mathbf{P}_m)\} \quad (6)$$

$\mathbf{P}_m$ is parameterized by four parameters which represent the coordinates of $\mathbf{P}_{m1}$ and $\mathbf{P}_{m2}$. The classical Newton method [22] is used to search for the optimal solution. Compute the optimal cost:

$$c_R(\mathbf{N}_{opt}) = c_{R1}(\mathbf{P}_{m,opt})$$

In step 2, solve the following optimization problem:

$$\{\mathbf{P}_{m3}, \mathbf{H}\}_{opt} = \arg\min_{\mathbf{P}_{m3},\mathbf{H}}\{c_{R2}(\mathbf{P}_{m3}, \mathbf{H}) + c_H(\mathbf{P}_{m3}, \mathbf{H})\} \quad (7)$$

$\{\mathbf{P}_{m3}$,$\mathbf{H}\}$ is parameterized by three parameters which represent the coordinates of $\mathbf{H}$ and the horizontal coordinate of $\mathbf{P}_{m3}$—the vertical coordinate of $\mathbf{P}_{m3}$ is the same to that of $\mathbf{H}$. The classical Newton method is also used to search for the optimal solution. Compute the optimal co-cost:

$$c_R(\mathbf{C}_{opt}) + c_H(\mathbf{C}_{opt}) = c_{R2}(\{\mathbf{P}_{m3}, \mathbf{H}\}_{opt}) + c_H(\{\mathbf{P}_{m3}, \mathbf{H}\}_{opt})$$

In step 3, compare $c_R(\mathbf{N}_{opt})$ with $c_R(\mathbf{C}_{opt}) + c_H(\mathbf{C}_{opt})$ to judge whether it is reasonable to exploit human cooperation.

### *D. Discussion*

*1) Perception of the environment:* Existing research works on motion planning (especially global motion planning) usually assumes the availability of enough environment knowledge, i.e. perception of the environment can be carried out in a way that satisfies the need of motion planning; here we also adopt this common assumption.

However, perception of the environment is by no means a trivial issue in real applications. A robot, if relying only on its on-board sensors, has rather limited view, which may deteriorate the effect of motion planning. In contrast, a robot may rely on the practice of *cooperative perception* to have enough perception of the environment: more specifically, surveillance sensors may be equipped in the environment—video surveillance has already been a common practice for many public places; other types of sensors such as laser scanners may also be used for surveillance purpose—these surveillance sensors can share their perception to the robot via communication techniques if the robot has such need. In this way, the robot would have an enlarged view, especially for environment parts that are directly occluded from the robot.

*2) From local optimization to global optimization:* Limited by computational resources and optimization techniques, only a local searching can be performed in the described instantiation of optimization solving. On the other hand, the proposed PCCMP is not limited to modelling cooperation cases that concern only local optimization. If global optimization can be efficiently performed, the PCCMP architecture has the capacity to model cooperation cases such as that the human may totally move away if the robot needs to pass by.

*3) Human motion cost:* By so far, the human motion cost is modelled as the distance that the human has to move to carry out the cooperation. In fact, an adaptive mechanism may be incorporated into the human motion cost model. For example, if the robot detects that the human is aged or is a pregnant woman, it can put more weight on their motion cost because they have more difficulty in moving. For another example, if the robot detects that the human is right busy with certain work which had better not be interrupted, it can put infinite weight on the human motion cost.

## IV. Simulation

### *A. Simulation scenario*

We present via simulation the performance of the instantiation of the PCCMP architecture described in section III, in order to demonstrate how this generic architecture can serve as a guide for the robot to decide whether to exploit human cooperation according to concrete scenario conditions. In the simulation, without loss of generality, we fixed the parameters of the robot and the human ($s_R$, $s_H$, $\{a_H$,$b_H\}$, and $\{a_R$,$b_R\}$), while mainly modifying the environment parameters (the left passage length $l_{PL}$, the right passage length $l_{PR}$, and the passage width $w_P$). We set $s_R$ and $s_H$ to 0.4m; set $\{a_H$,$b_H\}$ and $\{a_R$,$b_R\}$ to {0.5,1}.

### *B. Simulation results*

The instantiation described in section III was carried out under different $\{l_{PL}$,$l_{PR}$,$w_P\}$. Some simulation results are listed in Table I; the results associated with row 2-4 are visualized respectively in Fig.4, Fig.5, and Fig.6.

TABLE I. Simulation results under different $\{l_{PL}$,$l_{PR}$,$w_P\}$

| $\{l_{PL}$,$l_{PR}$,$w_P\}$ | $c_R(\mathbf{N}_{opt})$ | $c_R(\mathbf{C}_{opt}) + c_H(\mathbf{C}_{opt})$ | Exploit cooperation? |
|---|---|---|---|
| {8m,15m,2.4m} | 12.79 | 14.48 | no |
| {8m,25m,2.4m} | 22.64 | 14.48 | yes |
| {8m,15m,3.0m} | 11.83 | 11.56 | yes |
| {13m,20m,2.4m} | 17.79 | 19.46 | no |
| {13m,30m,2.4m} | 27.64 | 19.46 | yes |
| {13m,20m,3.0m} | 16.83 | 16.52 | yes |

Take Fig.4 (row 2) as an example. The red line in the right passage represents the optimal non-cooperative navigation process $\mathbf{N}_{opt}$. The yellow circle and the red line in the left passage represent the optimal potential cooperative navigation process $\mathbf{C}_{opt}$. The robot has the potential to pass via the left passage, if the human cooperates and moves to the position indicated by the yellow circle. However, since $c_R(\mathbf{C}_{opt}) + c_H(\mathbf{C}_{opt})$ is larger than $c_R(\mathbf{N}_{opt})$, the robot would still follow the right passage, instead of exploiting potential human cooperation in the left passage. In contrast, in the case shown in Fig.5 (row 3), the cost associated with the non-cooperative navigation process in the right passage is too high. In this case, the robot would rather exploit human cooperation in the left passage, as indicated by the solidness of the line in the left passage.

In the case shown in Fig.6 (row 4), the passage width is comparatively large, so the human and the robot have more space to fulfill the cooperation, without incurring much safety cost borne by them. According to the data in Table I, the robot would also prefer exploiting human cooperation in this case. Similar interpretation can be given to the results of row 5-7.

As we can see, following the PCCMP, the robot can make a decision according to concrete scenario conditions, instead of always making a rigid decision. If the detour is not so long whereas the cooperation will cause more inconvenience to the individuals, the robot would still take the detour, as in Fig. 4. On the other hand, if the detour is indeed too long or if the passage is wide so that the cooperation will not cause so much inconvenience, the robot would exploit potential cooperation to avoid the detour, as in Fig. 5 and 6. This *flexibility* of making a decision is rather similar to our daily experiences.

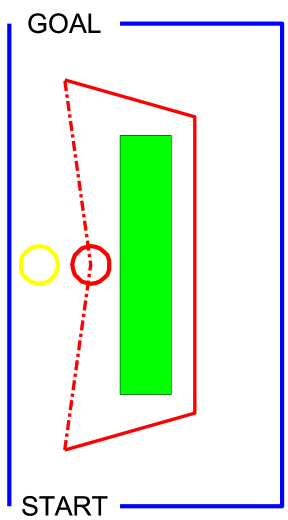


Fig. 4. Simulation result: $\{l_{PL},l_{PR},w_P\}$={8m,15m,2.4m}

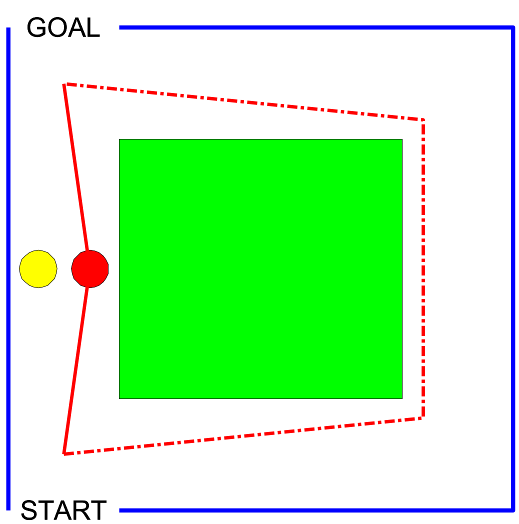


Fig. 5. Simulation result: $\{l_{PL},l_{PR},w_P\}$={8m,25m,2.4m}

### *C. Discussion*

Since cost modeling and optimization solving is out of the focus of this paper—in fact, these independent topics themselves deserve profound researches that are far beyond the scope of this paper—Despite the simpleness of the cost models and the milestone points based optimization solutions presented in section III, above simulation demonstrates that the PCCMP architecture provides a mechanism which enables the robot to *flexibly* decide whether to exploit human cooperation according to concrete scenario conditions, neither always neglecting potential human cooperation as in most related works, nor always exploiting human cooperation as in [14] [15].

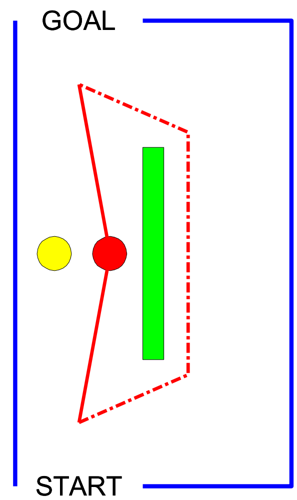


Fig. 6. Simulation result: $\{l_{PL},l_{PR},w_P\}$={8m,15m,3.0m}

It is true that an environment can be dynamic. For example, the human that currently blocks the left passage may move away later from the left passage for her/his own reason and hence make the left passage completely free. In this case, passing via the left passage is obviously better for the robot. However, the robot can not predict contingent events in future by itself. At current moment when the robot is at the START point and *has to* take a choice between following the left passage and following the right passage, the PCCMP architecture enables the robot to take a reasonable choice based on the robot's knowledge of current situation (including predictable events). In other words, although the reasonableness of the PCCMP based choice might be deteriorated by unpredictable events afterwards, yet such choice is reasonable at least at current moment when the choice has to be taken.

## V. Conclusion

In this paper, we have proposed the potential co-cost minimization principle (PCCMP) and the generic PCCMP architecture in the context of human aware robot navigation. We have described a concrete instantiation of the PCCMP architecture by specifying the cost modelling and the optimization solving. We have presented simulation results to demonstrate that the PCCMP architecture enables a robot to *flexibly* and *reasonably* decide whether to exploit human cooperation according to concrete scenario conditions.

Further improvements over the presented works are expected and can be carried out in following directions. First, the model parameters and even the model structure may be better designed by learning them from real data. Second, other path representation besides the milestone points based one presented may be adopted into the PCCMP architecture. Third, the presented instantiation of the PCCMP architecture is *ad hoc* for well structured scenarios; on the other hand, to develop an instantiation suitable for more general scenarios also deserve further research.

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