

Non-optimal Semi-autonomous Agent Behavior Policy Recognition

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Abstract: The coordination between cooperative autonomous agents is mainly based on knowing or estimating the behavior policy of each others. Most approaches assume that agents estimate the policies of the others by considering the optimal ones. Unfortunately, this assumption is not valid when an external entity changes the behavior of a semi-autonomous agent in a non-optimal way. We face such problems when an operator is guiding or tele-operating a system where many factors can affect his behavior such as stress, hesitations, preferences, etc. In such situations the recognition of the other agent policies becomes harder than usual since considering all situations of hesitations or stress is not feasible.

In this paper, we propose an approach able to recognize and predict future actions and behavior of such agents when they can follow any policy including non-optimal ones and different hesitations and preferences cases by using online learning techniques. The main idea of our approach is based on estimating, initially, the policy by the optimal one, then we update it according to the observed behavior to derive a new estimated policy. In this paper, we present three learning methods of updating policies, show their stability and efficiency and compare them with existing approaches.

1 INTRODUCTION

Recent developments on autonomous systems lead to a more consideration on limited capacities of sensing and acting in difficult environments to accomplish complex missions such as patrolling (Vorobeychik et al., 2012), security (Paruchuri et al., 2008) and search and rescue (Hüttenrauch and Severinsson Eklundh, 2006) applications. Introducing the human in the control loop is a challenging and promising research direction that attracts more and more researchers because it can help autonomous systems to perceive more information, to act more efficiently or to guide its behavior (Shiomi et al., 2008). Adjustable autonomy is the concept of considering different levels of autonomy from full autonomy to full tele-operation. A semi-autonomous agent is an agent following a policy where some human advice are considered. For example, an operator can send advice to a robot to avoid an area, or not to use an action on a specific state. When considering a system composed of semi-autonomous agents, the coordination of semi-autonomous agents becomes a challenging issue.

We are studying a multi-agent system, in which the agents can have different levels of autonomy: fully autonomous, semi-autonomous or tele-operated. The autonomous agents should compute a coordi-

nated policy considering the tele-operated and semi-autonomous agents. To this end, we consider the Leader-Follower (Panagou and Kumar, 2014) model. We focus, in this paper, on the situation where an autonomous agent (follower) should coordinate its behavior to a semi-autonomous or tele-operated agent (leader) where its policy is not known, but only actions and feedbacks from the environment are observed. We propose to use these observations to approximate the policy of the leader to compute the best-response policy of the follower using some existing algorithms such as Best-Response (Monderer and Shapley, 1996) or JESP (Nair et al., 2003). However, a semi-autonomous agent or a tele-operated agent do not, always, follow an optimal policy. Indeed, the operator may have preferences or hesitations which might influence the agent's policy, leading to a satisfying behavior rather than an optimal one. Trying to model each hesitation, or each preference is impossible, due to the high number of cases. That is why we consider an online model to learn the human behavior, based on the action selected by the operator.

The aim of this paper is to propose a new approach, based on a combination of Markov Decision Processes (Sigaud and Buffet, 2010) and Reinforcement learning (Sutton and Barto, 1998), to predict another agent's action when assuming that the optimal

one is not realistic. Indeed, we consider an approach where the optimal policy is initially assumed and by learning from previous actions, the initial policy is updated. We present three update methods: (i) the first method consists in learning from a complete history of the couples state and the last executed action, for all states; (ii) the second method consists in learning from the last executed actions the preferences of the human on the agent behavior considering a reward function update in all the state space; (iii) the third method is similar to the second method but focused only on a local update where only the states in the neighborhood of the current state, from which a deviation is observed, are considered.

The paper is organized as follow, in the second section we present the target applications, the third one is dedicated to the background necessary for the paper, the fourth section describes our approach, the fifth one presents the experiments and the obtained results and we finish the paper by a conclusion.

2 THE TARGET APPLICATIONS: SECURITY MISSIONS

Surveillance of Sensitive Sites with Robots. We consider a heterogeneous system composed of robots and operators for a surveillance mission of a sensitive site. The operators and robots can move from one checkpoint to another as a team, but an operator can send some advice to a robot to change its behavior and considers some constraints such as watching or not a specific area or it's desirable that the robot secure a hidden area (Abdel-Ilhah Mouaddib and Zilberstein, 2015), etc. The operator can also tele-operate a robot to head a specific point to get more accurate information with the onboard camera. The other robots fully autonomous have to adapt their behaviors to the tele-operated and the semi-autonomous ones while they don't know their policies if they didn't get information sent by the operators.

Maritime Coast Surveillance. In this example, we consider with our partners to deploy a fleet of UAV for watching the coasts where some UAV will receive from the control unit some advice about specific checkpoints while the other UAV should compute a coordinated policy to sweep all the coast for surveillance. Semi-autonomous UAVs compute their policies by considering the advice of the control unit while the autonomous UAV should adapt their behavior according to the semi-autonomous ones.

3 BACKGROUND

Markov Decision Processes: is a decision model for autonomous agent allowing us to derive an optimal policy dedicating to the agent the optimal action to perform at each state. More formally, an MDP is a tuple $\langle S, A, p, r \rangle$ where S is the state space and A is the action space. p is the transition function and r is the reward function. The expected value V^* maximization allows us to derive the optimal policy π^* using the Bellman equation (Pashenkova et al., 1996):

$$V^*(s) = \max_{a \in A} \sum_{s' \in S} p(s'|s, a)(r(s'|s, a) + V^*(s')) \quad (1)$$

$$\pi^*(s) = \operatorname{argmax}_{a \in A} \sum_{s' \in S} p(s'|s, a)(r(s'|s, a) + V^*(s')) \quad (2)$$

There exists many algorithms to solve this equation where the most popular are value iteration and policy iteration (Puterman, 1994). In our approach, we consider an MDP-based model.

Reinforcement Learning: is a method allowing an autonomous agent to adapt his behavior during the execution by updating his model.

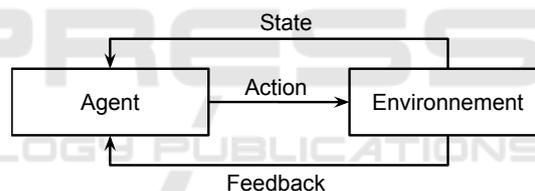


Figure 1: Representation of reinforcement learning.

The agent starts with an initial model to compute the policy to be followed during the execution. The execution of this initial policy leads to feed-backs from the environment, particularly the reward obtained after the execution. The obtained feed-backs allow us to update the model and to compute a new policy.

Many algorithms have been developed such as Q-learning (Watkins and Dayan, 1992), temporal difference $TD(\lambda)$ or SARSA (Sutton and Barto, 1998). Our approach uses a reinforcement learning similar to techniques with a reward function update procedure.

TAMER (Knox and Stone, 2008): is an algorithm used to train an agent with deterministic actions. It uses an MDP model without a reward function. An operator will train the robot by sending a positive or a negative signal H to the agent. This algorithm differs with what we want to do, because the agent needs to be trained before executing the algorithm. Moreover,

we are not trying to train an agent, but to learn his policy to adapt the observer behavior. We can, however, adapt the model by sending a positive reward for each state reached by the agent.

TAMER&RL(Knox and Stone, 2010)(Knox and Stone, 2012) is the computation between TAMER and a Reinforcement Learning method. It allows us to reduce the time of training.

Imitation Learning. Is a training method. The agent first observes an operator to complete the mission, and learns the policy with this observation. Many algorithms exist for imitation learning and presented in (He et al., 2012).

The idea of this algorithm is similar to our idea. However, the agent tries to learn the Master (leader in our case) policy to imitate him. In our approach we learn the Leader policy not to imitate him but to compute a best-response to better coordinate with him.

4 OUR APPROACH

The policy prediction is mainly based on series of policy estimation followed by a policy update. The observed agents are semi-autonomous or tele-operated. Consequently, the MDP model of the observed agent is already defined, even in the tele-operation case. First, we compute an optimal policy from their MDP model as an approximate initial policy and then we update it during the execution of this policy using the reinforcement learning techniques. Indeed, we, initially, assume that the Leader (the semi-autonomous agent) follows an optimal policy and when observing its behavior, we get information on the executed action, the rewarded value and the state $o = (a, r, s)$. When the observation o shows that the executed action a is different from the expected action $\pi(s)$, the autonomous agent (follower) updates the predicted policy π considering this deviation. The policy update to predict a new policy is based on three methods.

During the execution of the mission, the agent may choose different action from the estimated policy, due to the operators hesitations, preferences or perception. These changes are stored in a history H . Let $H_s(t)$ and $H_a(t)$ be respectively the history of the state and the action of the last operations up to time t . These histories represent the feed-backs of the environment during the last t operations which will be considered for updating the initial policy π_{init} . To this end, we will present three update methods to generate a new estimated policy π from π_{init} and $(H_s(t), H_a(t))$.

The "Force" Method. The idea behind this method is to update the current estimated policy by modifying some actions at some states using the history. Indeed, this method is a "forcing" approach where actions performed at some states in the last operations are introduced in the current estimated policy when a deviation from the estimated policy is observed. We assign, then, states in $H_s(t)$ with actions in $H_a(t)$, and then we compute the optimal actions for the other states not concerned with the changes to generate a new estimated policy. More formally :

$$\pi_{new} = \begin{cases} \forall 0 \leq k \leq t, s^k \in H_s(t) \text{ and } a^k \in H_a(t) : \\ \pi_{new}(s^k) = a^k \\ \forall s \notin H_s(t) : \pi_{new}(s) = \\ \operatorname{argmax}_{a \in A} \sum_{s' \in S} p(s'|s, a)(r(s'|s, a) + V^*(s')) \end{cases}$$

The "Learn" Method. Instead of the previous method where we change actions at some states of the current policy, this method is based on adapting the reward function to consider the preferences of the operator observed from the last previous operations. To this end, we assume that the operator acts to reach the desired and preferred states. More formally, we will define X as the set of n variables composing the states of the agent. Each of these variables $x_i \in X$ are defined in a domain D_i . The idea is to assign a reward to each variable which may interest the operator, and apply a cost for each variable which could be unpleasant to him. Then, by changing the reward function, the policy might evolve consequently. Let $x_i(s)$ be the value of the variable x_i from the state s , and let Q_i be the preference function for the operator for the variable x_i . $Q_i(v)$ is the reward function to the variable x_i when it takes the value v . Consequently, $Q_i(x_i(s))$ is the reward attributed to the variable x_i from the state s . Initially, every variables Q_i are set to 0, and c is the constant value to add to the reward function. The constant c might be chosen by considering the values on the reward function. With a high value, each action executed different from the estimated action will have a high impact on the policy update.

Algorithm 1 allows us to assign, to each successor state reachable from the deviation of the original policy, a reward according to the probability to reach it from the deviation. In the same way, we assign a cost for each state which should be reached by the current policy. To generate the new policy, we then compute a new reward function r' , with the equation 3. We then generate a new policy with the MDP $\langle S, A, p, r' \rangle$.

$$r'(s'|s, a) = r(s'|s, a) + \sum_{x_i \in X} Q_i(x_i(s')) \quad (3)$$

Algorithm 1: Reward update.

```

1 for  $t \in [0..k]$  do
2   if  $H_a(t) \neq \pi(H_s(t))$  then
3     for  $s'$  successor of  $(H_s(t), H_a(t))$  do
4       for  $i \in [0..n]$  do
5          $Q_i(x_i(s')) = Q_i(x_i(s')) +$ 
           $p(s'|H_s(t), H_a(t)) \times c;$ 
6       for  $s'$  successor of  $(H_s(t), \pi(H_s(t)))$  do
7         for  $i \in [0..n]$  do
8            $Q_i(x_i(s')) = Q_i(x_i(s')) -$ 
             $p(s'|H_s(t), \pi(H_s(t))) \times c;$ 

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Generalization: Consider a factored representation of states with n variables such that $s = (v_1, \dots, v_n)$, as depicted in Fig.2. The expected action at s is $\pi(s)$ leading to $s' = (v'_1, v'_2, \dots, v'_{n-1}, v'_n)$ while the semi-autonomous agent executes action $a(s)$ leading to $s'' = (v''_1, v''_2, \dots, v''_{n-1}, v''_n)$. Let's consider that s'' differs from s' at the first and the last variables. $v'_1 \neq v''_1$ and $v'_n \neq v''_n$ while the other variables are identical.

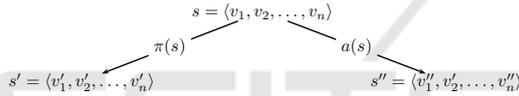


Figure 2: Representation of a derivation.

Learn method will increase the reward of all states $s = (v'_1, *, \dots, *, *)$ and $s = (*, *, \dots, *, v''_n)$ representing the preferred states of the operator and will reduce the reward of states $s = (v'_1, *, \dots, *, *)$ and $s = (*, *, \dots, *, v'_n)$ representing unpleasant states by assuming that the operator prefers $a(s)$ to $\pi(s)$ to reach preferred states with features v'_1 and v''_n rather than the ones with features v'_1 and v'_n .

Reward increase

$$r'(s = \langle v'_1, *, \dots, * \rangle) = r'(s) + Q_1(v'_1)$$

...

$$r'(s = \langle *, *, \dots, v''_n \rangle) = r'(s) + Q_n(v''_n)$$

Reward decrease

$$r'(s = \langle v'_1, *, \dots, * \rangle) = r'(s) - Q_1(v'_1)$$

...

$$r'(s = \langle *, *, \dots, v'_n \rangle) = r'(s) - Q_n(v'_n)$$

This algorithm estimates the operator preferences according to the concerned states. Meanwhile, when a deviation occurs, the reward update is propagated into the all state space and will affect the behavior policy of the semi-autonomous agent. This latter may overreact to derivations leading to the generation of more prediction errors than corrections, and then may create an unstable prediction process.

The "Dist" Method. This method is similar to the "Learn" Method by reducing the impact of the local updates. To this end, we should restrict the propagation to some states which are close to the updated state. To assess the closeness, we define the distance between two states in an MDP as the number of variables different from each other. Each state reachable by the predicted action will receive a cost and reversely. however, each state reachable by the predicted action will get a reward corresponding to the value of the parameters with reward for the observed action, in the condition that the distance between this state and another reachable by the observed action is less or equals to a threshold δ .

Generalization: We consider, at time t , that the operator derives from the predicted policy.

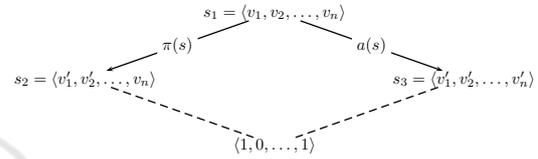


Figure 3: Calculation of a distance.

The distance between s' and s'' is 2 because $(v'_1, v'_2, \dots, v'_n)$ differs from $(v''_1, v''_2, \dots, v''_n)$ on variables v_1 and v_n . For example, if $\delta = 1$, considering s_o as a state reachable by the observed action and s_p as a state reachable by the predicted action, we will obtain the following modifications on the reward function:

$$r'(s'') = r(s'') + \sum_{i=1}^n Q_i(v''_i)$$

$$r'(s') = r(s') + \sum_{i=1}^n Q_i(v'_i)$$

$$r'(s_o = \langle v'_1, v'_2, \dots, v'_n \rangle) = r(s_o) + Q_n(v'_n)$$

...

$$r'(s_o = \langle v''_1, v''_2, \dots, v''_n \rangle) = r(s_o) + Q_1(v''_1)$$

$$r'(s_p = \langle v''_1, v''_2, \dots, v''_n \rangle) = r(s_p) + Q_n(v''_n)$$

...

$$r'(s_p = \langle v'_1, v'_2, \dots, v'_n \rangle) = r(s_p) + Q_1(v'_1)$$

The first two equations are about decreasing the reward for the states reachable by the estimated action and increasing the reward for the ones reachable by the executed action. The next two equations represent the increase of states closed to the ones reachable by the executed actions, oppositely to the last two ones.

5 EXPERIMENTS

We develop experiments to show the efficiency and the impact of the operator hesitation on the prediction to show the robustness of the methods to the operator mistakes. We also develop experiments on the impact of δ in the Dist method to assess their performances. We consider two kinds of environments of

the site surveillance, an indoor environments where the robots evolve in a restricted space and an outdoor environment where the space is open and there is a limited impact of locality. We consider that in these environments the areas have three levels of lighting from very bright to dark leading the agent to select the right actions (using the right sensor) to better behave. An optimal policy allows the agent to use the best action at a state according to the lighting level and when the agent uses an action different from the optimal one, it gets a cost. The mission of the agent is to start at a location and targets a new one for surveillance. We formalize the tele-operation process of the agent by an MDP. To simulate the operator preferences, we will force the MDP policy to choose one action on specific states (to force the agent to follow or to avoid a path) before generating the optimal policy. To formalize the hesitation, we define probabilistic policies, in which the operator selects probabilistically some actions at some states. During the execution, we used the learning methods described above to predict the behavior of the semi-autonomous agent, and compare the prediction results. To evaluate their efficiency, we consider the number of prediction errors made by each prediction method.

We also compare these methods with an adapted TAMER&RL (TAMER combined with SARSA(λ)), on which the learning algorithm will receive a reward for each action dictated by the operator to the semi-autonomous agent. TAMER&RL was configured with the Table 1. "Learn" and "Dist" methods are configured with the following parameters $c = 3$ and $k = 10$.

Table 1: Configuration of TAMER&RL.

Parameter	value
TAMER	
α	0.2
SARSA-LAMBDA:	
α	0.8
ϵ	0
γ	1
λ	1
β	0.98

5.1 Results in Indoor Environments

During the experiments, we recorded the number of prediction errors during the 50 executions of the missions. In this experiment, we compare the algorithms in different situations: deterministic and stochastic actions, operator doesn't hesitate representing an expert and self-control operator, operator hesitates frequently representing a non-expert operator and operator hesitates sometimes representing an expert oper-

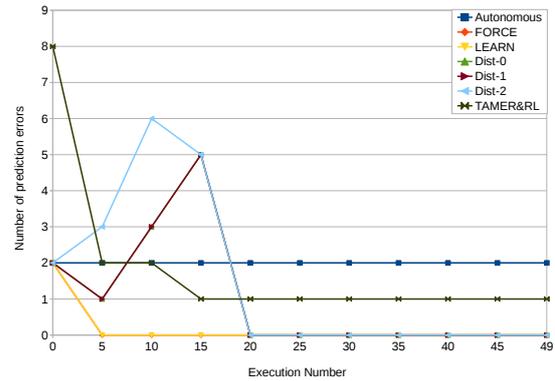


Figure 4: Results with no hesitation.

ator, but can make some mistakes in some stressed situations.

Without Hesitation: Expert and Self-control Operator. Fig.4 represents the number of prediction errors according to the number of the mission execution. The autonomous curve corresponds to the optimal policy of an autonomous agent, without learning during the execution. This algorithm is used here to show the impact of learning. Note that "Dist-i" corresponds to the "Dist" method, with $\delta=i$.

We can see that almost all curves converge to 0, which means that almost all algorithms learn correctly the agent policy. The only exception is TAMER&RL, which keeps one prediction error over the time. However, it's under the autonomous curve. TAMER&RL starts with a high number of prediction error because the algorithm starts the learning from scratch without considering the past mission executions. "Force" and "Learn" curves are similar in this case, and they converge quickly. However, we can see that "Dist" methods are not stable, in the beginning, but they converge and find the agent policy after some periods of time. To conclude, our methods outperform TAMER&RL and converge more quickly.

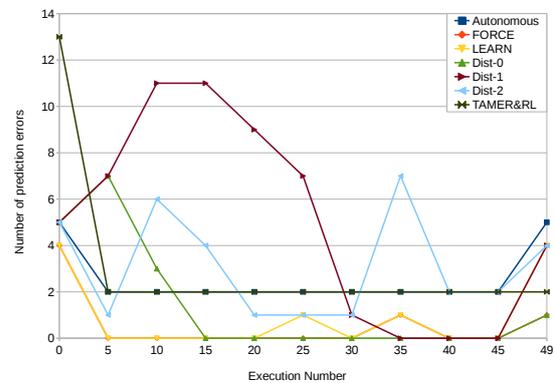


Figure 5: Results with 30% hesitation on some states.

With 30% Hesitation: Non-expert Operator. We can see in Fig.5 that the prediction methods are more unstable during the whole execution, except for the "Learn", "Force" and TAMER&RL methods. "Learn" and "Force" curves are similar and converge, but they still get few errors in some cases. However, these algorithms learn globally the agent policy. "Dist" methods are more unstable than before, and get a lot of prediction errors at the beginning. The only one who seems to be stable is for $\delta = 0$. The others seem to be close to the agent policy, but each variation on the agent policy generates many perturbations on the prediction. The "Learn" method does not present a high number of mistakes, but he is much perturbed by hesitations than the "Force" or the TAMER&RL methods. The "Force" method gets an error every time the agent changes the action of the policy at a state. Otherwise he is the most efficient.

Impact of Stochastic Transitions. For the experiments, we first used deterministic actions to compare the results with TAMER&RL, because this method needs deterministic transitions. We repeated the experiments to see the impact of stochastic transitions, to analyze the robustness of the different algorithms. To do so, we adapted the TAMER&RL policy by considering the stochastic transition function.

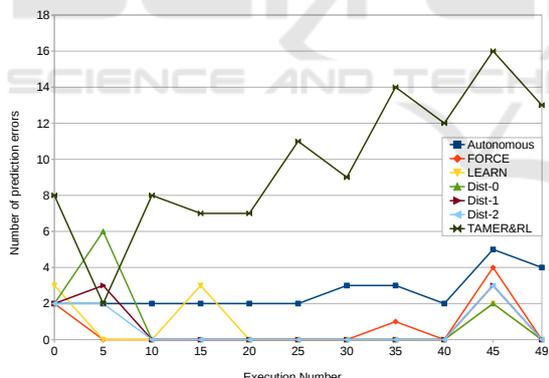


Figure 6: Results without hesitation, but with stochastic actions.

We can see in Fig.6 that TAMER&RL does not present the same results with stochastic transitions. Indeed, TAMER&RL seems inappropriate for learning if transitions are not deterministic. All our approaches outperform TAMER&RL. On the other hand, without hesitation, "Dist" methods seems to be more efficient with stochastic transitions than deterministic ones. The reason may be that each transition leads to several states, so the Dist methods learn on more states, but still locally.

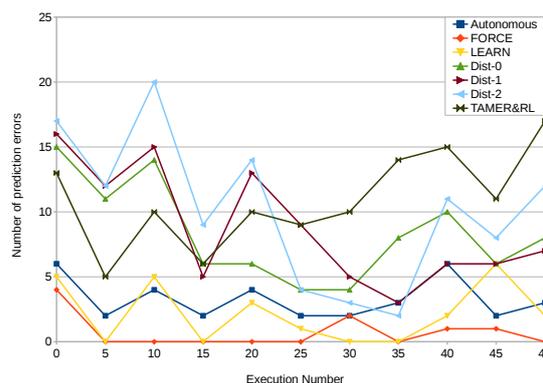


Figure 7: Results with 30% hesitation, but with stochastic actions.

On Fig.7, we can see that with a high rate of hesitations, every method get unstable. This is not surprising because it implies a lot of execution changes. For each time a new state is reached, each time the pilot policy can derive from the autonomous policy. It implies a lot of policy modifications to learn. The "Force" and the "Learn" methods seem predict well. However, "Dist" methods and TAMER&RL are totally unstable and does not predict well. "Dist" methods seem to learn after the 20th execution. This is due to the fact that a lot of new states were reached between the 35th and the 40th, since every method started to get prediction errors at this moment.

Nevertheless the hesitation is implemented by choosing between two actions randomly. Moreover, the agent policy is generated with transition functions adapted with hesitation, but an operator would not know when he will have doubts, and doesn't know his probability to choose an action at this moment. Furthermore, the hesitations rate may decrease over the time since the operator learns also from his previous experiments of the mission.

5.2 Results in Outdoor Environment

We developed a new serie of experiments in outdoor environment where the branching factor in the state space is high.

With 0% Hesitation: Expert and Self-control Operator. We can see in Fig.8 that the "Force" method is still better than the others including TAMER&RL. "Learn" method is not as efficient as in restricted space, and is less efficient than the autonomous policy. The reason is that in such environments the branching factor is high and the number of states reachable from the current one is high. Then, updating the operator preferences in all the state space may

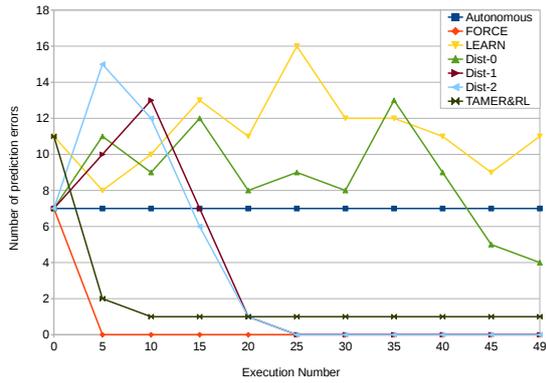


Figure 8: Results with 0% hesitation on an open space, with deterministic actions.

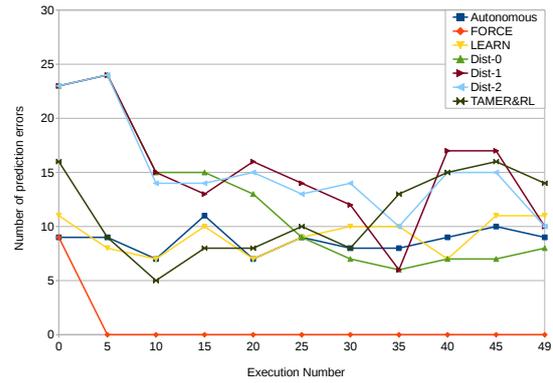


Figure 10: Results without hesitation in an open space with stochastic transitions.

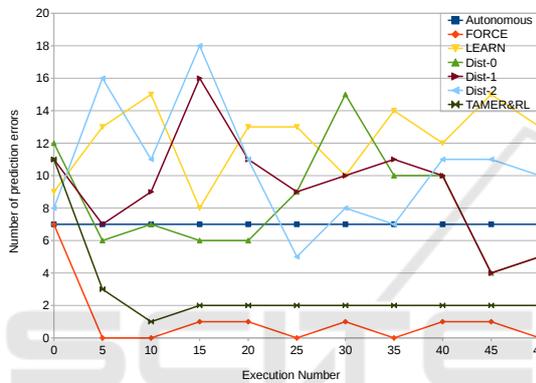


Figure 9: Results with 30% hesitation in an open deterministic space.

impact all the policy, while in indoor environments the state space is restricted. By limiting the learning field, "Dist" method avoids this effect and learns the agent policy, except with a $\delta=0$.

With 30% Hesitation: Non-expert Operator. With hesitation, on Fig.9, almost no method, excepted TAMER&RL and "Force" method, can predict correctly the agent policy. "Dist" methods show best results than "Learn", but they are still less efficient than the autonomous policy. Indeed, when the operator is not stable is difficult to learn from this behavior the operator preferences while maintaining a policy with local update is better because it's still not far from the optimal policy which in such cases are suitable.

Impact of Stochastic Transitions. With stochastic transitions on Fig.10, as expected, TAMER&RL cannot predict anything, and Force method remain efficient. The other policy predictions are unstable, and less efficient than the optimal policy, excepted Dist-0.

5.3 Synthesis

The table 2 shows the efficiency of each method in different cases. ++ means that the method learns quickly the policy. + Means that the algorithm learns the policy, but the convergence is slow, and - means that the algorithm is not efficient. However, "Force" is efficient in any situation. "Learn" is efficient only with restricted environments, such as indoor ones. TAMER&RL is efficient on deterministic transitions, but there exist a more efficient alternative in any situation. "Dist" method is much efficient without hesitations. Also, in indoor environments, it works better with stochastic transitions. However, in outdoor environments, the algorithm is efficient only when in deterministic transition cases.

6 CONCLUSION

We addressed in this paper the problem of estimating the policy of a semi-autonomous agent where this latter could follow a policy other than the optimal one. To this end, we develop an approach based on initializing the policy to the optimal one and then update this policy according to the observed behavior and the operator actions. We propose three update methods to predict the next behavior of the system by estimating the new policy. These methods are based on the history of the last operations to change the current policy or to update the reward function. We distinguished between a method propagating the reward update in the whole state space and a method restricting the propagation to subspace by defining a notion of distance among states.

The experiments show satisfying and promising results and showing a robustness to the operator mistakes in indoor environments, except for the "Dist"

Table 2: Efficiency of prediction methods, considering the situation.

environment	Indoor				Outdoor			
	Det.		Stoc.		Det.		Stoc.	
	no	yes	no	yes	no	yes	no	yes
Force	++	++	++	++	++	++	++	++
Learn	++	++	++	+	-	-	-	-
Dist	+	+	++	-	++	-	-	-
TAMER&RL	+	+	-	-	+	+	-	-

method who learns mistakes and take a lot of time before learning. TAMER&RL is much stable with deterministic actions than "Force" and "Learn" methods, but less efficient. In stochastic transition cases, TAMER&RL is outperformed by every other method. In outdoor environment, "Dist" method seems to be much adapted, contrary to "Learn" method.

In short-term, we will integrate our methods in a multi-robot system, developed in a national project, on the sensitive site surveillance example where a robot is tele-operated by a professional operator and the other should predict its policy and compute a coordinated policy to head the same destination.

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