Mixed-Initiative Human-Robot Interaction: Definition, Taxonomy, and Survey

Shu Jiang and Ronald C. Arkin
School of Interactive Computing
Georgia Institute of Technology
Atlanta, GA, USA

***Abstract*—The objectives of this article are: 1) to present a taxonomy for mixed-initiative human-robot interaction and 2) to survey its state of practice through the examination of past research along each taxonomical dimension. The paper starts with some definitions of mixed-initiative interaction (MII) from the perspective of human-computer interaction (HCI) to introduce the basic concepts of MII. We then synthesize these definitions to the robotic context for mixed-initiative human-robot teams. A taxonomy for mixed-initiative in human-robot interaction is then presented. The goal of the taxonomy is to inform the design of mixed-initiative human-robot systems by identifying key elements of these systems. The state of practice of mixed-initiative human-robot interaction is then surveyed and examined along each taxonomical dimension.**

Keywords—mixed-initiative interaction; taxonomy; survey; human-robot interaction; human-robot team

I. INTRODUCTION

Dull, dirty, and dangerous tasks have long been deemed perfectly suited for robots. We have seen an increase in recent years in the use of robots for dangerous emergency response situations (i.e., harmful for human lives) that range from natural disasters (e.g., Fukushima nuclear plant meltdown [1]) to terrorist attacks (e.g., the World Trade Center (WTC) disaster [2]). These dangerous situations call for human-robot teams such that the robots are typically teleoperated by one or more operators at a remote location, away from the danger zone. However, this distance creates a disconnect between human and robot that presents some unique challenges for effective collaboration within the human-robot team (e.g., situational awareness, time delay).

Furthermore, characteristics of emergency disaster response situations escalate the issues for effective human-robot remote collaboration. The robot's operating environment can be uncertain, unstructured, and hostile. The damaged Fukushima nuclear plant's high radiation level not only posed danger to humans, but to robots without radiation-hardened electronics as well [1]. Typical disaster sites caused by earthquakes are permeated with rubble piles, confined spaces, and unstable structures can greatly impair a robot's mobility and perceptual capabilities [3]. Lack of reliable communication is another typical characteristic of a disaster-struck environment. Most robots deployed for urban search and rescue (USAR) were tethered [4]. In fact, the only robot that was lost in World Trade Center disaster response was a wireless robot [5].

Critical emergency situations also put first responders under constant stress that can lead to mistakes while operating/supervising the robots. Many sources of human errors (e.g., lack of feedback, invalid internal models) have been identified in [6]. Murphy [5] described first responders' physiological conditions as tired, dirty, and stressed. For USAR, the first 48 hours is crucial for finding and extracting victims, thus it is not unusual for emergency first responders to go days without sleeping [5]. This causes fatigue and makes first responders more error-prone while operating robots. Another stressor involves high-stake risks that are associated with disaster response missions, where failures can have catastrophic consequences (e.g., biological attacks).

While both human and robot have their own respective limitations when operating under the extreme conditions of disaster response missions, they each also have a set of complementary skills that if interleaved properly, can enable the human and robot to collaborate as an effective team. Mixed-initiative interaction has been proposed as an interaction strategy where members of a team can interleave their control of a mission based on their respective skill sets [7-9]. The basic idea of mixed-initiative interaction is to let the team member who knows the best at achieving the mission objectives take the lead in mission execution. However, challenges still remain for building effective mixed-initiative human-robot systems. The paper presents a taxonomy for mixed-initiative human-robot interaction and surveys the state of practice through the examination of past research along each taxonomical dimension.

II. DEFINITION

Mixed-initiative interaction first appeared in the domain of human-computer interaction (HCI) for building intelligent conversational agents. The first known reference to the term mixed-initiative was by Carbonell in 1970 [10], in which the author associated the term with a computer-assisted instruction (CAI) system that was designed to maintain a dialogue with students during instruction [11]. While several definitions for mixed-initiative interaction have been offered since then, there is still no consensus [12, 13]. The most prominent definitions of mixed-initiative interaction were proposed by Cohen et al. [12], Allen [7], and Horvitz [9]. However, these definitions are specific to the HCI domain, where the objective is to use mixed-initiative interaction as a model for building intelligent collaborative conversational, problem solving, and planning systems [14-17].

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Allen [7] believed that mixed-initiative interaction lets agents work most effectively as a team. He [7] defined mixed initiative interaction as "*a flexible interaction strategy where each agent can contribute to the task that it can do best. Furthermore, in the most general cases, the agents' roles are not determined in advance, but opportunistically negotiated between them as the problem is being solved*." The basic idea is to let the agent who knows best at solving the problem to coordinate the other agents. Horvitz [9] argued that mixed-initiative enhances human-computer interaction (HCI) by allowing computers to behave more like partners who are capable of working with users and contributing to the problem-solving process. Horvitz [9] defines mixed-initiative interaction as "*the methods that explicitly support an efficient, natural interleaving of contribution by users and automated services aimed at converging on solutions to problems*." The common thread of Allen's and Horvitz's definitions is the idea of *interleaving contributions*, where each agent contributes to the solution based on its knowledge and skills.

While the above definitions introduce the basic concepts of mixed-initiative interaction, they lack a clear/explicit notion of what "initiative" actually is. According the Oxford dictionary, initiative is defined as "the power or *opportunity to act or take charge before others do*" [18]. This definition connotes the concept of taking up the leadership role, which echoes what Allen's definition implies [7]. Cohen et al. [12] presented different definitions of initiative, specifically for intelligent conversational and problem solving agents: 1) "*control over the flow of conversation*" 2) "exercising *of the power to perform a task for solving a problem*", and 3) "*seizing control of a conversation by presenting a goal to achieve*". However, these definitions have not been integrated into a more comprehensive definition of mixed-initiative interaction.

Mixed-initiative interaction was first introduced to the domain of human-robot teams in 1997 by Kortenkamp et al. [19] as a new planning perspective for traded control tasks. However, the definition of mixed-initiative interaction has not been clearly defined in the robotic context. Most work on mixed-initiative interaction for robotics either do not define its meaning or simply adopt existing definitions from the HCI community [19, 20], which has focused on building intelligent conversational and problem-solving agents. However, collaboration in the robotic context raises many different challenging issues other than the ones encountered in the HCI domain (e.g., operating in uncertain and hostile environment, lack of situational awareness and reliable communication for remote teams). Existing definitions of initiative also do not emphasize that an initiative is *mixed* only when each member of the team is authorized to intervene and seize the initiative from the current initiative holder. This could result in mixed-initiative systems that are heavily one-sided and human-centered; that is, only the human can intervene to seize initiative from the robot while the robot cannot seize control from the human operator; which is evident in the state of practice presented in Section IV. Furthermore, as an indication of a lack of clear consensus on the application of mixed-initiative interaction to the robotic context, researchers [21-23] have designed mixed-initiative human-robot systems that we believe are not truly mixed-initiative according to existing design philosophies and principles (e.g., opportunistic intervention) of mixed-initiative interaction. Thus, what mixed-initiative interaction means for human-robot teamwork needs to be clearly defined in order to provide a clear vision of an effective mixed-initiative human-robot team, on which research efforts can be focused on to realize. Based on the definitions of mixed-initiative interaction given by Horvtiz [9] and Allen [7], and the theories of initiative from Cohen et al. [12], we synthesized them into a definition for mixed-initiative human-robot interaction (MI-HRI) as:

> *A collaboration strategy for human-robot teams where humans and robots opportunistically seize (relinquish) initiative from (to) each other as a mission is being executed, where initiative is an element of the mission that can range from low-level motion control of the robot to high-level specification of mission goals, and the initiative is mixed only when each member is authorized to intervene and seize control of it.*

This definition is more comprehensive than other definitions in the literature since it both succinctly captures the key idea of opportunistic intervention of mixed-initiative interaction and clearly defines what initiative means in a robotic context.

III. Taxonomy

The construction of the taxonomy centers around three simple yet fundamental questions one may ask when examining a mixed-initiative human-robot system, whose answers can provide a comprehensive characterization of the system, stated informally: 1) What is the initiative? 2) When does the robot/human take the initiative? 3) How does the human/robot take the initiative?

A. First Dimension – What is the Initiative?

We have defined initiative as a control element of a mission that can range from low-level motion control to high-level planning and goal setting. Therefore, the 'what' question asks which elements of a mission that both the human and robot of a particular human-robot team are authorized to control and intervene the other when necessary. Different types of initiative that may exist depends on the mission the human-robot team is required to accomplish and how the mission is decomposed into subtasks/subgoals. Initiative can be associated with each subtask as in Guinn's proposal [15] of attaching initiative to each mutual goal. Chu-Carrol and Brown [24] also argued that only maintaining a single initiative is insufficient for modeling complex behaviors that affect an intelligent agent's decision making process during interaction with human. The idea is that by distinguishing between different types of initiative, the mixed-initiative system can behave more appropriately based on the context and model of the initiative.

Our definition of mixed-initiative emphasizes and argues the notion that an initiative is *mixed* when both human and robot have the authority to not only control the initiative but to opportunistically seize the initiative from the other when necessary. This follows the spirit of mixed-initiative interaction: *interleaving contributions through opportunistic intervention*, and allows the team member who is best at the task at the moment to take charge of the task. Therefore, we consider the first dimension of the taxonomy as characterizing the extent of initiatives that are *mixed*, or the initiatives that both human and robot are authorized to intervene and take control from the other as needed. We called this dimension ***span of mixed-initiative***.

The process to accomplish a mission/task can generally be divided into three phases [11]: 1) Goal Setting – the process of setting the goal for the mission to achieve, 2) Planning – the process of constructing a plan to achieve the goal, and 3) Execution – the process of carrying out the mission by following the plan. An initiative then can be attached to each mission phase such that each team member can seize control of the mission process by taking the initiative. As a result, each member of the human-robot team can have a set of initiatives that consists of any one or more of these three phases. Thus, given the sets of human and robot initiatives, I_{Human} and I_{Robot}, the *span of mixed-initiative* characterizes the intersection of I_{Human} and I_{Robot}, or how *mixed* are the initiatives of the human-robot team, and can be defined in terms of the order of the intersection of I_{Human} and I_{Robot}, or the number of elements that are in the intersection:

1. ***Disjoint*** – the order of the intersection $I_{Human} \cap I_{Robot}$ is 0, or no initiative is mixed within the human and robot team (e.g., I_{Human}={Goal Setting, Planning}, I_{Robot}={Execution})
2. ***Slightly-Joint*** – the order of intersection is 1, or exactly one element of the mission initiative is mixed within the human and robot team
3. ***Mostly-Joint*** – the order of intersection is 2, or two elements of the mission initiatives are mixed within the human and robot team
4. ***Significantly-Joint*** – the order of intersection is 3, or all three mission initiatives are mixed within the human-robot team (i.e., I_{Human}=I_{Robot}={Goal Setting, Planning, Execution})

B. *Second Dimension – When to Seize Initiative?*

Timing is everything; ill-timed intervention would be ill-fated. Timing is especially important for critical missions, where poorly timed intervention/interruption could have catastrophic consequences. Horvitz [25] identified poor timing of actions taken as one of the deficiencies of the current mixed-initiative agents. The 'when' question is concerned with the timing issue for mixed-initiative human-robot interaction by asking when does the robot take (relinquish) initiative from (to) the human, and vice versa?

Adam et al. [11] suggested some triggers that may cause the robot to take initiative away from the human (e.g., when the human is drowsy, sleepy, or dangerously inattentive). Allen [7] argued that each agent should continuously monitor the current task and evaluate whether it should take the initiative in the interaction based on: agent's capability, other demands on the agent, and evaluations of other agents' capabilities. At a more subtle level, however, the 'when' question is more concerned with how does one agent (human or robot) determine when to take initiative from the other agent; i.e., what is the underlying mechanism that determines the 'when'. For instance, how does the robot recognize that the human operator is performing poorly on the task? And how does the robot determine that it is a better suited member to take control? Furthermore, the "when" question encapsulates two fundamental characteristics of mixed-initiative human-robot interaction:

- *Interleaved Contributions* – human and robot interleave their contribution to the common goal by contributing to the task that it can do best
- *Opportunistic Intervention* – both human and robot reasons about whether to seize (relinquish) initiative from (to) the other and determines the appropriate window of opportunity for intervention

Interleaving of contributions reflects the basic idea of mixed-initiative interaction by letting who is best at the task do that task. While effective interleaving of contributions is a desired manifestation of the mixed-initiative system, opportunistic intervention is a requirement to achieve such a desired effect. That means a successful mixed-initiative human-robot team would require an inherent capability of the mixed-initiative system for recognizing the opportunity (i.e., when) to assist the human operator (or ask for help) during a collaborative task in a timely manner. Thus, we include a second taxonomical dimension to characterize the mixed-initiative system through its ability in recognizing intervention opportunities for seizing (relinquishing) initiative from (to) the human operator. We call this dimension ***initiative reasoning capacity***, which characterizes the ability of the robot for *reasoning about the opportune moment* to seize (relinquish) initiative from (to) the human operator, and define the dimension with three discrete categories (similar to categories of robot control [26]): ***reactive***, ***deliberative***, and ***hybrid***.

Reasoning is "*the process of thinking about something in a logical way in order to form a conclusion or judgment*" [18]. ***Reactive*** mixed-initiative systems employ no such reasoning process for determining when to seize initiative from the human operator. The action of taking initiative is tightly coupled to, hence typically triggered by, some external stimuli (e.g., sensors, event monitoring systems, etc) without the use of intervening abstract knowledge representation, or explicit modeling of the context (e.g., the environment, task, and operator). The advantage of reactive systems is their ability to respond rapidly to critical emergency events that afford no time for deliberation. This allows the robot to respond very quickly to seize safety critical initiatives that are required to address the dangerous challenges of real world missions such as a hostile environment [5], time delay [4], loss of communication [27], etc. However, for an intervening point that is not so readily recognizable through direct sensory events, "careful thought" is required for the robot to make the decision of when to take the initiative. ***Deliberative*** mixed-initiative systems reason about the potential costs and benefits of initiative actions (i.e., whether to take/relinquish initiative) based on the knowledge, or inferred state, of the context, which includes but is not limited to: operator state [11, 28] and needs [29, 30], task status, and environmental conditions. Deliberative reasoning allows the robot to infer optimal actions in light of costs, benefits, and uncertainties [25]. The goal of *initiative reasoning* is to identify the most appropriate intervention point in time in order to intervene appropriately and least invasively to improve performance rather than to impede progress. Lastly, ***Hybrid*** initiative reasoning, as its name implies, combines reactive and deliberative reasoning to allow the system deliberation on initiative action, but also rapidly respond to critical events as needed.

C. Third Dimension – How to Seize Initiative?

The fundamental idea of mixed-initiative interaction is to let the best-suited member of the team take control of the task (i.e., the initiative). In order to realize this idea, the initiative is shifted between team members based on who is the best-suited member at a given moment in time. However, the handoff process had been recognized as a point of vulnerability during team collaboration [31, 32]; i.e., the team is susceptible to errors during the shift of initiative, and consequently may experience degraded performance. Therefore, initiative handoff between team members needs to be carried out with care to ensure successful shift of initiative, and to prevent breakdown in teamwork and initiative to be lost in transition. The 'how' question is concerned with the issue of initiative handoff by asking how does the mixed-initiative team handoff initiative from one member to the other (e.g., human to robot, and vice versa).

Solet et al. [33] defined handoff as the "*transfer of role and responsibility from one person to another in a physical or mental process*". Examples of handoff range from mundane daily occurrences of effortless object handover between humans to critical handoff situations such as in patient care [31, 33]. Errors in handoff of patients have been found to be a contributing factor to preventable injuries and deaths in U.S. hospitals [33] . For instance, the wrong leg of a Florida man was amputated due to miscommunications during the handoff of the patient [31]. Errors in shift handoff had also been identified as the causal factors for disastrous incidents in other high-risk domains[34]. Furthermore, distributed teams, where team members are distributed geographically, present additional challenges for initiative handoffs due to the absence of co-location (e.g., team opacity and coordination decrement [35]). Thus, it is imperative for a mixed-initiative team to employ coordination strategies to ensure smooth and successful shift of initiative. Therefore, we present the third dimension of mixed-initiative interaction, ***initiative handoff coordination,*** to characterize the strategies a mixed-initiative system employs to coordinate the shift of initiative between team members.

Based on the literature on the coordination of human teams, coordination strategies can be classified into two general categories: *explicit coordination* and *implicit coordination* [35]. We adopted these categorizations for initiative handoff coordination. ***Explicit coordination*** refers to activities undertaken overtly by team members for managing and orchestrating the process of initiative handoff, mostly executed by means of communication. Examples of explicit coordination include: attempts to control teammates' actions through explicit commands, requests for information, questioning decision, following initiative handoff protocols, warning before taking the initiative, and appropriate feedback, etc. The failure to communicate explicitly has been linked to failures and accidents in aviation [36]. ***Implicit coordination*** is the ability of the team members to act in concert, where team members anticipate the actions of teammates and dynamically adjust behavior accordingly, usually without the need for overt communication [37]. Examples of implicit coordination behaviors include [38]: 1) anticipatory offering of information to a teammate with explicit request and 2) dynamic adjustment of ongoing actions in anticipation of others' actions. However, implicit coordination is only effective if and only if team members have an accurate shared understanding of each others' needs, responsibilities, and expected actions (i.e., a shared mental model), and a common mental image of the situation and the status of the joint-task (i.e., common ground or shared situational awareness) [36]. Furthermore, recent literature has shown that effective teams switch between explicit and implicit coordination when under stressful conditions (e.g., increased workload) [36, 39]. Thus, ***adaptive coordination*** is another category of *initiative handoff coordination*. The concept of adaptive coordination implies that different coordination mechanisms are appropriate in different situations. The core idea of adaptive coordination lies in the dynamic use of coordination mechanisms in accordance with the given situation. Lastly, some mixed-initiative systems do not consider or employ coordination strategies when shifting initiative between team members (e.g., the initiative taker simply does not inform other members when taking initiative). Thus, ***no coordination*** is an additional category for *initiative handoff coordination*.

D. Discussion

The three taxonomical dimensions of mixed-initiative human-robot interaction, presented above, originated from the three basic questions of "what", "when", and "how" that authors asked when examining the literature of mixed-initiative human-robot teams. While there are other potential dimensions that can also be considered for the taxonomy (e.g., interaction modality, robot autonomy, etc), they belong to a more general taxonomy (e.g., Yanco [40]) of human-robot team/interaction. Thus, the presented taxonomical dimensions provide a succinct characterization of mixed-initiative systems without overloading the taxonomy. The resulting taxonomy also forms a three-level tree where a mixed-initiative system can be classified to one of its leaves (e.g., slightly-joint, reactive, and not coordinated) (Fig. 1).

IV. SURVEY

This section surveys the state of practice of mixed-initiative human-robot teams through the examination of past research along each of taxonomical dimension presented in the previous section. The goal is to identify gaps posing significant remaining challenges for building effective mixed-initiative human-robot teams.

A. *Disjoint*

Disjoint mixed-initiative systems are human-robot teams where the team members have disjoint sets of initiatives, i.e., no initiative is shared between the human and robot. While disjoint systems are technically not mixed-initiative systems according to our definition, we include them here for completeness since their authors had defined these systems as mixed-initiative. Furthermore, these systems can illustrate and differentiate non-mixed-initiative human-robot teams from teams that we considered to be mixed-initiative according to the definition we presented in Section II.

There are generally two types of disjoint-initiative systems. The first type is where the initiatives of the human-robot team are allocated ahead of time and remain unchanged afterwards. The initiatives of these systems do not shift between team members during task execution. Thus, these systems lack the key characteristic of "*opportunistic intervention*" of mixed-initiative interaction. For instance, Murphy et al. [21] developed a mixed-initiative human-robot system for urban search and rescue (USAR), where the robot takes the initiative of the perceptual task of looking for victims while the human operator has the initiative of the navigational task. However, the system is more of fixed-initiative than a mixed-initiative since each team member's initiative is allocated ahead of time and remains fixed rather than *opportunistically negotiated* during mission execution. That is, the robot does not take over control of navigation from the human, and the human does not take over control of the perceptual task from the robot. The initiatives of the human and robot are *disjoint*.

The second type of disjoint-initiative systems are the ones where the initiatives are one-sided and human-centered; that is, while the operator can intervene the robot whenever she thinks necessary, the robot cannot intervene the operator at all. This also violates the principle of mixed-initiative interaction that each team member can seize initiative from the other as needed. For instance, Finzi et al. [41] presented a reactive mixed-initiative planning approach for human-robot interaction for a USAR mission. The interaction with the system is controlled by the human operator, thus the operator decides when the shift of initiative happens (i.e., whenever she intervenes). The reactive controller monitors the systems' low level status and the operator's interventions by continuously performing the sense-plan-act cycle. The autonomy of the robot is dependent on how often the operator interacts with the system. Without human intervention, the system would follow its own plan, thus act like an autonomous agent. On the other extreme of the spectrum where the operator intervenes very frequently, the robot would keep re-planning and act under close guidance of the human operator. Similarly, Wang et al. [42] presented a mixed-initiative human-robot team where, while the robots can autonomously explore the world, the operator was free to intervene with any individual robot by issuing new waypoints, teleoperating, or panning/tilting its camera. The robot returned back to the autonomous mode once the operator's command was completed or stopped.

Bresina and Morris [43] presented MAPGEN, a successful mixed initiative planner deployed as a mission critical component of the ground operations systems for the Mars Exploration Rover mission. However, all of the initiative is on the side of the user since all planning operations are triggered by the user. Clare et al. [44] presented a mixed-initiative scheduling system, where a human guides a planner in a collaborative process to solve the scheduling problem of assigning task to UVs. The system allows the operator to influence the planning process by changing objective functions for the automated planner to use in evaluating mission plans. Pereira and Sousa [45] considered mixed-initiative interactions, where human operators are able to tune parameters of the problem according to their experience. The system allows the operator to constrain re-allocations, to increase or decrease the frequency of re-allocations or even to force re-allocations to happen.

In the controls community, mixed-initiative interaction has been interpreted as methods for incorporating human input in generating control commands for the robot. Such interpretation typically resulted in disjoint mixed-initiative human-robot teams. For instance, Loizou & Kumar [46] presented an approach for composing behaviors resulting from human inputs with behaviors derived from navigation functions. Under the influence of the user input (i.e., direction and velocity commands) and the navigation vector field, the robot was guided to its destination. Chipalkatty et al. [47] presents a method for injecting human inputs into mixed-initiative interactions between humans and robots. The method is based on a model-predictive control (MPC) formulation, which involves predicting the system (robot dynamics as well as human input) into the future. The control law was designed to minimize deviations from the human input, while also ensuring that the state constraints are satisfied.

B. *Slightly-Joint, Reactive, Not Coordinated*

Slightly-joint, reactive, not coordinated mixed-initiative systems are human-robot teams where the human and robot share one initiative element, the shift of initiative is triggered by immediate sensory events, and no coordination strategies are used for the handoff of initiative between team members. The most common examples of these systems are systems where the robot has the initiative to protect itself (e.g., obstacle avoidance). For instance, Horiguchi and Sawaragi [48] presented a teleoperation system where mixed-initiative interaction was enabled through a force-feedback joystick. The initiative level of the human is determined by the force she exerts on the joystick. The robot also exerts force on the joystick to restrict the operator's input based on its perception of the environment (e.g., obstacles). The resultant force then determines how the robot moves in the environment. While the joystick interface provides a mean for both human and robot to take initiative depends on the situation, the interface is limited to low-level control of robot motion. Similarly, in Nielsen et al. [22], a human-robot team is tasked with the mission to explore a building and locate two radiation sources, where the operator controlled the robot via a joystick and the robot was given initiative to prevent collisions with obstacles by inhibiting movement towards detected obstacles. Ali and Arkin [49] presented a schema-based approach for incorporating human and robot contributions to the overall behavior of a robot team in executing tasks.

Hardin et al. [50] presented a mixed-initiative interaction that allows both the human operator and the agent to decide the correct level of autonomy for a given situation. However, the autonomy of the agents was limited to a search and exploration behavior. The shift of initiative is reactive and is caused by two triggers: 1) operator specifying a search area and 2) the robot decided to search an area based on its own information. Few et al. [23] presented a standard shared mode (SSM) for human-robot team, where the robot accepts operator intervention in the form of intermittent directional commands and supports dialogue through the use of a finite number of scripted suggestions (e.g., "path blocked! Continue left for right?") and other text messages that appear in a text box within the graphical interface. A guarded motion behavior permits the robot to take initiative to avoid collisions by scaling down its speed using an event horizon calculation based on its laser and sonar sensor readings. And the operator may override the translational and/or rotational behavior of the robot at any time by moving the joystick.

C. Slightly-Joint, Deliberative, Not Coordinated

Slightly-joint, deliberative, not coordinated mixed-initiative systems are human-robot teams where the human and robot share one initiative element, the shift of initiative is determined through deliberative reasoning, and no coordination strategies are used for the handoff of initiative between team members. Manikonda et al. [51] presented a mixed-initiative controller for human robot teams in tactical operations. Each human/robot agent in the framework maintains a model of the world state, the state of the robot team and the state of the robot/humans they are supporting. The framework adopted a simple probabilistic model for the "cognitive" model of the human. The robot agents use information from onboard sensors and other members of the team to update their internal representation of the world, robot agents, and human agents, and to predict the human's intent. Based on these state updates and predictions, the robots then take the initiative to dynamically modify their goals. These new goals are then mediated with other agents and may require approval from the human depending on the authority of particular robot agent. Once the goals are approved, re-planning occurs to generate a new set of partial plans.

D. Slightly-Joint, Hybrid, Explicitly Coordinated

Slightly-joint, hybrid, explicitly coordinated mixed-initiative systems are human-robot teams where the human and robot share one initiative element, the shift of initiative can either be triggered by immediate sensory events or determined through deliberative reasoning, and explicit coordination strategies are used for the handoff of initiative between team members. Bruemmer et al. [28] presented a mixed-initiative command and control architecture for remote teleoperation of robotic systems in hazardous environments. The control architecture includes four modes of remote intervention: teleoperation, safe mode, shared control, and full autonomy. However, mixed initiative control is only available at safe and shared control modes, where the robot has the initiative of low-level navigation and obstacle avoidances. Furthermore, Bruemmer et al. [28] have endowed a "theory of human behavior" within the robot's reasoning capacity, which allows the robot to switch modes when the robot recognizes that the human is performing very poorly, which is based primarily on the frequency of human input and the number and kind of dangerous commands issued by the user. Lastly, Bruemmer et al. [28] argued for the need of appropriate feedback when roles and levels of initiative changes and proposed some ways to coordinate the shift of initiative (e.g., robot could state that it is taking control of the task and allow the human veto power to this initiative).

E. Completely-Joint, Deliberative, Not Coordinated

Completely-joint, deliberative, explicitly coordinated mixed-initiative systems are human-robot teams where the human and robot share all initiative elements, the shift of initiative is determined through deliberative reasoning, and explicit coordination strategies are used for the handoff of initiative between team members. Adam et al. [11] presented a mixed-initiative human-robot collaboration architecture, where all elements of initiatives are shared between the human and the robot. Within the architecture, mixed-initiative interaction starts at the HRI level where either the human or robot assumes initiative to dynamically determine the mission goals and constraints. At the planning level, the steps to accomplish the given mission (i.e., goals and constraints) are outlined and validated with human and robot. At the execution level, the plan is sequentially executed and either human or robot is allowed to intervene in the execution sequence. Adam et al. [11] used affective sensing to infer the state of the human operator, which in turn is used to determine whether the robot should seize the initiative from the operator. The human's affective state is inferred from physiological signals, which are measured using biofeedback sensors (cardiac activity, electro-thermal response, etc). For example, if the robot detects extreme stress or panic in the human, the robot may take the initiative to rescue the human from a risky situation or abort the mission. However, in Adam et al. [11], no initiative handoff coordination strategy is considered beyond the explicit rule that the human gains the initiative when there is a conflict.

F. Summary

The taxonomical categorization of past research on mixed-initiative human-robot teams is summarized in Fig. 1. The figure offers several observations regarding the paradigm's state of practice. First, there is a limited amount of research in applying the concept of mixed-initiative interaction to the domain of human-robot teamwork. However, this limitation presents copious new research opportunities which, if addressed properly, could result in significant progress in the paradigm of human-robot teaming. Second, a significant number of the surveyed mixed-initiative human-robot systems are disjoint (i.e., no initiative is mixed within the human and robot team). This can be mostly attributed to their respective authors' interpretation of mixed-initiative interaction for the robotic domain. This further justified our motivation for synthesizing a new definition of mixed-initiative interaction for the domain of human-robot teams. Third, the majority of the mixed-initiative systems are limited to sharing control authority for one initiative element (i.e., low span of mixed-initiative), typically motion control of the robot. This is partially due to the limitation of the capabilities of current robotic systems. Furthermore, the complexity of a mixed-initiative system would increase significantly when more initiative elements are shared within the human-robot team. Fourth, current mixed-initiative systems have an inadequate consideration of the costs and benefits of their actions [25]. Furthermore, uncertainties of the human goals, mission states, and the environment make the initiative reasoning even more challenging. Lastly, the majority of the mixed-initiative systems are not coordinated during initiative handoff since most researchers have focused on the "when" issue of taking initiative as opposed to the "how" issue. However, Tecuci [8] identified the problem of employing appropriate strategies for shifting the initiative and control between the human and the robot as a major issue for mixed-initiative interaction. Furthermore, Bruemmer et al. [28] cautioned that the interaction between the human and the robot during initiative shift needs to be designed according to principles of human factors, otherwise, shift in initiative and control may result in loss of situational awareness, degraded performance, and catastrophic failure. Moreover, taking control from a human is a delicate issue that if not coordinated properly can lead to distrust and hinder the acceptance of the technology.

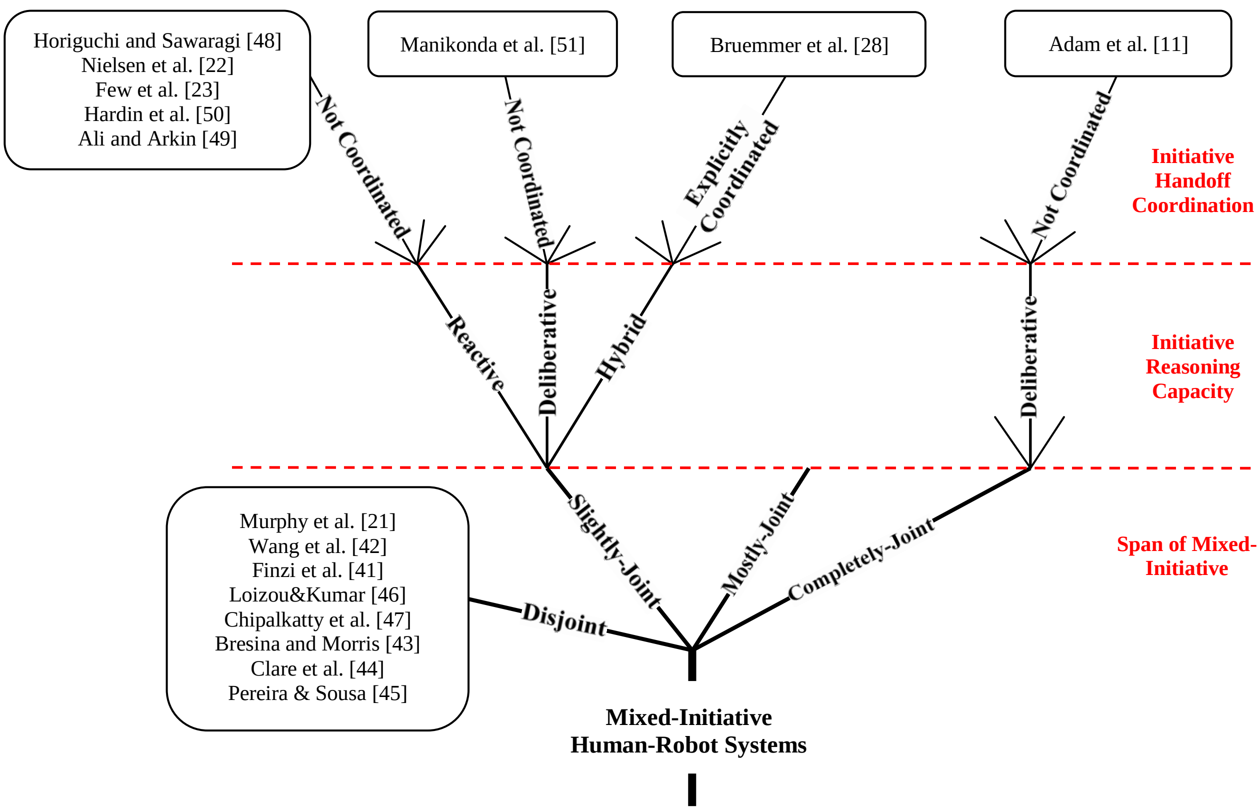

Figure 4: Categorization of Mixed-Initiative Human-Robot Teams

V. Conclusions

Developing robots that can work alongside humans as partners remains a major challenge for roboticists. Mixed-initiative interaction has been proposed as an effective collaboration strategy that enables the human and the robot to work together to achieve a common goal in a way that exploits their complementary capabilities through efficient interleaving of contributions. While mixed initiative interaction promises to enable tightly synchronized collaborations of humans and robotic systems [25], it has not to date been applied to the robotics domain in a way that fully exploits its true potential to realize such teamwork. This paper examined mixed-initiative interaction as an effective collaboration strategy for human-robot teams. We first synthesized a definition of mixed-initiative interaction for the domain of human-robot teamwork based on existing definitions from the HCI domain. We then presented a taxonomy for mixed-initiative human-robot interaction (MI-HRI) and surveyed its state of practice through the examination of past research along each taxonomical dimension.

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