Modelling intent for Manned-Unmanned Teaming

Exploring human-centric approaches for future combat aircraft systems

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Linköping 2022
Abstract

What does it mean to understand intent? This question is at the core of resilient teamwork since team members must account for each other’s intent in anticipated as well as unanticipated situations to adaptively coordinate their actions. As we enter an era where humans and synthetic agents are supposed to work as teammates, this question is brought to its head. For instance, unmanned aircraft are expected to act as human-like wingmen in the near future, requiring them to account for and adapt to the lead fighter pilot’s intent in various contexts and situations with little or no communication. To this end, adequate models of fighter pilots’ intent are crucial for enabling synthetic wingmen to reason about what their partner is doing, why, and what will happen next. Unfortunately, the concept of intent is often ambiguous and approaches to model intent are rarely described. As a result, researchers and practitioners often rely on assumptions regarding what aspects and elements of intent should be modelled—and how to approach the problem of modelling intent.

This thesis addresses the what and how to model intent from a human-centric perspective by defining and operationalising the concept of intent and suggesting three novel and complementary approaches. Additionally, by applying the approaches to model fighter pilot intent in the context of Manned-Unmanned Teaming, both methodological considerations when modelling intent and design implications for future applications are presented.
Svensk sammanfattning


Denna avhandling behandlar vad och hur man kan modellera intentioner från ett människocentrerat perspektiv genom att definiera och operationalisera begreppet intention och föreslå tre nya och kompletterande tillvägagångssätt. Dessutom, genom att tillämpa tillvägagångssätt- ten för att modellera stridspilotintentioner i samband med Manned-Unmanned Teaming, presenteras både metodologiska överväganden vid modellering av intentioner och designimplikationer för framtidiga tillämpningar.
Acknowledgement

I once was asked what I was doing in my work. After thinking a while, I answered, “I am trying to understand fighter pilots”. Thinking about it, I am trying to understand what they intend to do and do intentionally. In this sense, I may have the same questions as unmanned aircraft ought to have if they are supposed to work as human-like wingmen. Addressing these questions in my research, I am thankful to those who made it possible to walk this path.

First and foremost, I wish to thank my SAAB Aeronautics managers for providing me with the opportunity to grow in this undertaking and for continuously showing support and interest in my work. I am also grateful to my supervisor and co-supervisor at Linköping University, Jonas Lundberg and Björn Johansson, who showed me a research landscape and helped me shape a path. I am also grateful to my co-supervisor at SAAB Aeronautics, Jens Alfredson, who motivated me to walk the path and clear the obstructions along the way. Last but not least, I am grateful to my family, Madeleine, for her patience and support, and Cornelia for coming into our lives.

Jimmy Hammarbäck
Linköping, November 2022
List of papers

This compilation thesis is based on the following manuscripts. Throughout the thesis, these manuscripts will be referred to as Paper X, where X refers to the roman number of the paper. Note that interview data from Study 1 is used in Paper I and Paper II, while interview data from Study 2 is used in Paper III.


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Chapter I
Introduction

This chapter sets the stage for this thesis by motivating its long-term purpose and aim, followed by a problem analysis resulting in three research questions, how they are addressed, and their contributions. Additionally, the research perspective and scope are clarified, ending with outlining the structure of this thesis.

Motivation

With advances in artificial intelligence, machine learning, and cognitive modelling, the concept of humans and synthetic agents working as teammates transitions from merely conceptual to increasingly practical and applicable (O’Neill, McNeese, Barron, & Schelble, 2020). Following this transition, it has been argued that we are entering a new interaction paradigm, where embedded and embodied synthetic agents are no longer perceived as tools— but as teammates (Rix, 2022). Such hybrid teaming envisions taking advantage of the emergent effects resulting from humans and synthetic agents working collaboratively (Lyons, Sycara, Lewis, & Capiola, 2021).

In aviation, this paradigm shift can be seen on the horizon as increasingly autonomous unmanned aircraft are expected to act as human-like wingmen by the year 2040 (Department of Defence, 2018; Endsley, 2015; Jordan, 2021). Such Manned-Unmanned Teaming envisions combining the inherent strengths of fighter pilots and synthetic wingmen with operational synergies, effectively supporting shared situation awareness, engendering calibrated trust, easing interactions and control, and balancing workload for mission success (Endsley, 2015).

To reach this state, one of the long-term goals is to develop capabilities for aircraft systems to interpret human mission planning and action (Department of Defence, 2018). Such intent-aware systems have been argued to be able to represent fighter pilots’ current and future behaviour without explicit communication; enabling aircraft systems to allocate authorised control of planning and execution, detect and resolve conflicting intent, and provide timely distribution of information (Geddes & Lizza, 2001) as well as fostering partnership (Suck & Fortmann, 2016).
Purpose, aim, and research questions

Granted the advantages that intent-aware aircraft systems can have in future Manned-Unmanned Teaming contexts, the long-term purpose motivating this thesis is:

**Purpose**  
*Support the design of future intent-aware aircraft systems in the context of Manned-Unmanned Teaming.*

Considering this long-term purpose, adequate intent models are crucial for enabling synthetic wingmen to reason about what fighter pilots are doing, why they are doing it, and what they will do next (Sukthankar, Goldman, Geib, Pynadath, & Bui, 2014). Unfortunately, efforts to model human intent are often technology-centric, using techniques such as graph models (Geddes, 1994) and Hidden Markov models (Suck & Fortmann, 2016). That said—what about the human? This question was posited by Baltrush and colleagues (2022), arguing for a shift from imposed collaboration to a more human-centric collaboration. Indeed, taking an even broader perspective, synthetic agents in a teaming context should be designed from the perspective of being a teammate rather than a replacement, requiring both human and artificial intelligence considerations (Zhang, McNeese, Freeman, & Musick, 2021). To this end, a more holistic perspective for modelling intent is necessary (Hiatt, Narber, Bekele, Khemlani, & Trafton, 2017; Van-Horenbeke & Peer, 2021), in which human factors approaches can provide novel insights for enabling intent-aware synthetic wingmen. Thus, the aim of this work is:

**Aim**  
*Support the design, analysis, and evaluation of intent models from a human-centric perspective.*

Three research questions were identified through a problem analysis to achieve this aim. The following sub-sections briefly motivate and describe these research questions, how they are addressed and their contributions.
Define and operationalise intent

Aiming to support the design, analysis, and evaluation of intent models from a human-centric perspective, the first question becomes—What is supposed to be modelled? In research, the concept of intent is often ambiguous or inconsistent, as it is rarely defined or defined contradictorily. For instance, Bratman (1987) points out that intent can characterise both mental states and actions as agents intend to do things and do things intentionally. In this regard, there is clearly a relationship between these characterisations of intent; however, the nature of this relationship is unclear. Likewise, the concept of intent has been described in terms of goals (Han, 2013), plans (Bratman, 1987), a combination of desires and beliefs (Davidson, 1963), and even as broadly as a purpose or aim with all of its connotations (Pigeau & McCann, 2000, 2006). Considering the ambiguities and contradictions associated with the concept of intent, the first research question is:

**RQ1** What aspects and elements of intent should be considered when modelling intent?

Addressing RQ1, a literature review related to frameworks and models of intent was conducted to define and operationalise the concept of intent in terms of its nature, functional roles, and content. The expected contribution is to facilitate a better understanding of the concept, particularly aspects and elements of intent that should be considered when modelling intent from a human-centric perspective.

Explore approaches to model intent

With a better understanding of the concept of intent, the next question becomes—How can intent be modelled from a human-centric perspective? Indeed, as noted earlier, modelling intent is often technology-centric, in which communities use a plethora of modelling techniques (Albrecht & Stone, 2018; Sukthankar et al., 2014). This notion, together with the observation that the process to inform such models is rarely, if ever, described (Norling, 2008), suggests that researchers and practitioners seem to rely on assumptions when modelling intent. In this regard, taking the perspective that human factors approaches can provide means to model intent and explicate how fighter pilots reason and behave in the first place, the second research question is:
RQ2  *How can intent be modelled from a human-centric perspective?*

To address RQ2, the author of this thesis set out to explore various human factors approaches to design, analyse, and evaluate models of fighter pilot intent from a human-centric perspective. The expected contribution addressing this question is a better understanding of how researchers and practitioners can approach the problem of modelling intent to gain insights and inform models necessary for enabling synthetic agents to reason about fighter pilot behaviour.

**Model to learn and learn from models**

Although there are examples where human factors approaches have been suggested for enabling synthetic agents to reason about human behaviour (Norling, 2009), the purpose of these has usually been to inform the implemented models. That said, modelling and models can have several purposes; for instance, it has been argued that one can learn more from designing and manipulating models than from looking at them (Morgan & Morrison, 1999), motivating the third research question:

RQ3  *What was learned from designing, analysing and evaluating intent models using the explored approaches?*

Addressing RQ3, by taking the perspective that one can learn from modelling intent as well as learn from intent models, the author of this thesis set out to gain insight that can further support researchers and practitioners in the same or similar domains. The expected contribution from these are methodological recommendations for modelling intent from a human-centric perspective and design considerations for future Manned-Unmanned Teaming, thus directly relating to the purpose and aim of this thesis.
Adopting a research stance

A hermeneutic phenomenological approach was adopted to model fighter pilot intent from a human-centric perspective in a context where future Manned-Unmanned Teaming is envisioned. As a phenomenological approach, structures of experiences and consciousness are studied (Kafle, 2013; Laverty, 2003) in which intent in practical reasoning and actions are of particular interest. This approach also fits well with Bratman’s (1987) notion that it is more useful to study norms and regularities in which intent is implicated rather than engage in linguistic inquiries or hard problems. Such notions also characterise the macro-cognitive perspective (Klein et al., 2003), which seeks to identify patterns of cognition in more naturalistic settings rather than study micro-cognitive functions in labs. Consequently, when considering the contributions of this thesis, these ought to be considered from the adopted research stance.

Scope and delimitations

Although several frameworks and models were used to define and operationalise the concept of intent in this work, how the definition and operationalising hold in other domains is outside the scope of this thesis.

Additionally, modelling intent is often associated with various techniques used in intent, plan, and activity recognition; however, this work aims to support the design, analysis, and evaluation of intent models from a human-centric perspective. Thus, the implementation of intent models is outside the scope of this work; however, they may inform implementations to enable future aircraft systems to reason about fighter pilots’ behaviour.

While this work has identified design considerations for future Manned-Unmanned Teaming applications, implementing and evaluating these considerations is outside the scope of this thesis. That said, they can provide ideas and possible directions for future work.
Thesis outline

This section briefly describes the parts that make up this thesis.

Chapter I Introduction
This chapter sets the stage and motivates this thesis, describing the long-term purpose, aim, and three research questions.

Chapter II Theoretical background
This chapter describes the theoretical background, focusing on topics related to hybrid teaming and intent modelling.

Chapter III Understanding the domain
This chapter introduces the domain in which this work is situated, focusing on the context in which Manned-Unmanned Teaming is implicated.

Chapter IV Methodology
This chapter presents the methodological approach used to address the long-term purpose, aim, and research questions in this thesis.

Chapter V Summaries of papers
This chapter summarises the included papers, including motivation, method, conclusions, and main contributions.

Chapter VI Discussion
This chapter discusses the main contributions related to RQ1-RQ3 and includes the definition and operationalisation of intent, the explored approaches, as well as methodological and design considerations.

Chapter VII Conclusions
This chapter concludes this thesis by revisiting the long-term purpose and aim, and how this thesis has contributed to these.
Chapter II
Theoretical background

This chapter introduces the teaming concept—with a focus on hybrid teaming—and is followed by an overview of intent and intent modelling since these topics are at the centre stage of this thesis.

Teams, teamwork, and team performance

Teams are prevalent in numerous domains and have been noted as the ‘strategy of choice’ to cope with complex and difficult tasks (Salas, Cooke, & Rosen, 2008). Although the concept of a team has been defined in various ways, it has traditionally been characterised in terms of membership, interdependence, goals, roles, dynamic interactions, and boundaries (Benishek & Lazzara, 2019). For instance, a commonly used definition of a team is:

“A distinguishable set of two or more people who interact dynamically, interdependently, and adaptively toward a common and valued goal/object/mission, who have each been assigned specific roles or functions to perform, and who have a limited life-span of membership.” (Salas et al., p. 4)

This definition has also been argued to capture the essence of teamwork—multiple individuals, interdependencies, and a shared goal (Salas, Shuffler, Thayer, Bedwell, & Lazzara, 2015). As a concept, teamwork is closely related to collaboration, cooperation and coordination (Bedwell et al., 2012). For instance, Bedwell et al. (2012, p. 130) defined collaboration as:

“an evolving process whereby two or more social entities actively and reciprocally engage in joint activities aimed at achieving at least one shared goal.”

As such, teamwork is noted to be an instantiation of collaboration where teamwork is analysed at a team level, whereas collaboration allows multi-level analysis (e.g. collaboration between individuals, groups,
units, organisations, societies, or any cross-level combination thereof. In this sense, not all collaboration involves teamwork. Cooperation is often used interchangeably with collaboration; however, it has been suggested to denote an attitude (or predisposition) towards the overall collective goals (Bedwell et al., 2012), capturing the motivational drive of effective teamwork (Salas et al., 2015).

Coordination is often used to describe collaboration at a team level, referring to the sequences and timing of interdependencies (Bedwell et al., 2012) or the enactment of cognitive and behavioural mechanisms necessary to transform resources into outcomes (Salas et al., 2015). On this note, team members perform both taskwork and teamwork processes, where the former is independent of others’ performance while the latter is interdependent. Consequently, teamwork can be understood as an instantiation of collaboration which involves both cooperation, as an attitudinal construct, and coordination, as a means for managing cognitive and behavioural dependencies and interdependencies.

Team performance can be understood as the emergent state that arises from team members performing taskwork and teamwork processes to manage dependencies and interdependencies at individual and team levels (Salas et al., 2008). As such, team performance emerges as the dynamic interaction of elements (e.g. cognition and behaviour) and is shaped, constrained, and influenced by context (Kozlowski & Klein, 2000).

**Hybrid teaming**

Hybrid, or mixed, teaming here refers to humans and synthetic agents working as teammates. In this context, synthetic agents should be understood as embedded or embodied autonomous entities situated in an environment where they can perceive and act (Heinze, 2004). Although hybrid teaming has gained popularity in research in recent years (see Figure 1), the concept has been around for decades, recognised under different names. For instance, simple searches on the Scopus database reveal more than 5300 results by combining words in the format Human+[agent, ai, automation, autonomy, machine, robot]+[collaboration, cooperation, coordination, teaming, teamwork], with the earliest example from 1984. Among the most common concepts are Human-Robot collaboration (e.g. Bauer, Wollherr, & Buss, 2008) and Human-Machine cooperation (e.g. Hoc, 2000).
In recent years, the concept of Human-Autonomy Teaming has become the modern vernacular describing hybrid teaming (O’Neill et al., 2020), defined as:

“interdependence in activity and outcomes involving one or more humans and one or more autonomous agents, wherein each human and autonomous agent is recognized as a unique team member occupying a distinct role on the team, and in which the members strive to achieve a common goal as a collective.” (O’Neill et al., 2020, p. 8)

As such, it shares common characteristics of the teamwork concept; however, the Autonomy aspects of Human-Autonomy Teaming beg some questions in the context of Human-Autonomy Teaming. For instance, Who is Autonomy, What is Autonomy, and Why use Autonomy? These questions are addressed in the following sections.
Who is Autonomy?

In the context of Human-Autonomy Teaming, Autonomy, as a synthetic teammate, refers to:

“a computer-based entity that is recognized as occupying a distinct team member role.” (O’Neill et al., 2020, p. 28).

As noted in this definition, Human-Autonomy Teaming literature often emphasises that synthetic agents ought to be perceived as teammates rather than tools, assistants or subordinates. For instance, in a review by Rix (2022), it is pointed out that the increased capabilities offered by recent advances challenge the traditional perception of systems as tools, as these advances have the potential for a new interaction paradigm where they have agentic and collaborative characteristics. Similarly, O’Neill et al. (2020) argue that synthetic agents should be perceived as having a degree of agency, expressed through independence, self-governance, and proactivity. Similarly, Wynne and Lyons (2018) suggested a model with six dimensions of agent team-likeness (agentic capability, benevolent/altruistic intent, task interdependence, task-independent relationship building, richness of communication, and synchronised mental models) to further the research and discussion of perceiving synthetic agents as teammates.

What is Autonomy?

Although hybrid teaming assumes highly autonomous synthetic agents, the concept of ‘autonomy’ is often associated with confusion and misconceptions leading to erroneous assumptions. For instance, it has been noted that autonomy and automation are sometimes used interchangeably (Vagia, Transeth and Fjerdingen, 2016; O’Neill et al., 2020). Indeed, several taxonomies have been proposed in which levels of automation and autonomy are often used similarly to indicate a degree of function capability and responsibility in interactions (Vagia, Transeth, & Fjerdingen, 2016). However, this conceptualisation is not unproblematic (e.g. Bradshaw, Hoffman, Woods, & Johnson, 2013); for instance, as pointed out by Bradshaw et al. (2012), autonomy does not characterise a system but rather emerges as the result of interaction with the system, the task, and the situation.
Furthermore, autonomy has been argued to be a multi-dimensional concept. For instance, Castelfranchi (2000) described different dimensions of autonomy in terms of various social and non-social dependencies. Correspondingly, Bradshaw and colleagues (2004) suggested two dimensions of autonomy: self-sufficiency and self-directness. In this regard, self-sufficiency refers to a descriptive dimension of what entities can do in the situation, whereas self-directedness refers to a prescriptive dimension of what entities are permitted to do. Similarly, Kaber (2018) suggested three dimensions: viability in the environment, self-governance over defining goals and formulating strategies, and independence as the capacity to perform functions without assistance. Additionally, from a teaming perspective, it is important to recognise that interdependence contributes to shape autonomy (Johnson et al., 2011). For instance, team members are interdependent on their potential, possible, and performable actions and their relation to permissibility, availability, and achievability (Bradshaw et al., 2004). Taken together, it is important to recognise that autonomy is neither a system nor a uni-dimensional concept—but rather an emergent state that may vary as a function of the context, input, process, and output (Marks, Mathieu and Zaccaro, 2001).

**Why use Autonomy?**

Albeit advances make hybrid teaming more practical and applicable, in these research efforts, there is also an underlying assumption that this will benefit teams, teamwork, and team performance. For instance, it has been argued that hybrid teaming is more representative of human-human teaming, where humans and synthetic agents interact as peers rather than supervisors and subordinates (McNeese, Demir, Cooke, & Myers, 2018). If so, why not continue with human-human teaming?

To answer this, there are two main reasons. First, to substitute humans in dangerous tasks (Endsley, 2017) or in situations where no human is available (Lyons & Havig, 2014). Second, to complement human capabilities collaboratively (Cummings, 2014), where the emergent effects are more than what would be expected from human-human teaming (Lyons et al., 2021). Thus, from the perspective of hybrid teaming in this thesis, it may provide opportunities to substitute and complement humans in different situations, but it does not necessarily entail that this is neither practical nor applicable. Indeed, as noted by Schelble and colleagues (2020), there are many aspects to consider when integrating hybrid teaming in applied settings.
Current research in hybrid teaming

Although hybrid teaming provides opportunities, numerous challenges persist. For instance, in a review of human-robot collaboration, Baltrusch and colleagues (2022) identified four categories of factors affecting job qualities: cognitive workload, collaboration fluency, trust, and acceptance and satisfaction. Similarly, in a review of empirical research in Human-Autonomy Teaming, variables related to team and individual performance, workload, trust, situation awareness, team coordination, and shared mental models were prevalent (O’Neill et al., 2020). While a brief overview, these reviews hint at current challenges in hybrid teaming.

Addressing these challenges, researchers have focused their work on areas such as bi-directional communication, bi-directional (or teamwork) transparency, and various control methods. For instance, it has been argued that bi-directional communication is necessary for a shared understanding of the mission space and task coordination (Marathe, Schaefer, Evans, & Metcalfe, 2018). Additionally, bi-directional communication may facilitate shared situation awareness and engender trust (Schaefer, Straub, Chen, Putney, & Evans, 2017), in which a shared semantic space can support a shared mental model (Schneider & Miller, 2018). Although transparency has traditionally been focused on supporting the human awareness of the synthetic agents’ state and intent, recently, the notion of bi-directional (or teamwork) transparency has been introduced (Chen et al., 2018). Indeed, although not described explicitly, it has been argued that transparency should foster shared awareness and intent (Lyons, 2013; Lyons & Havig, 2014). In order to coordinate work, several control approaches have also been suggested; for instance, function allocation, adjustable autonomy, mixed-initiative interactions, and collaborative control (Johnson et al., 2011). Roth and colleagues (2019) suggested methods beyond the traditional functional allocations for exploring the distribution of work in a trade-space. Similarly, Calhoun and colleagues (2018) suggested design principles for an adaptive control approach allowing for more flexible task delegation and a balanced workload. Albeit not obvious from these examples in current research, one common denominator for the challenges and how these are addressed is the notion of intent, which is also the main topic in this thesis. Thus, motivating a better understanding of what is meant by intent.
Making sense of intent

Albeit not always apparent, the concept of intent is central in our experiences of the world—from reasoning about how to act (Bratman, 1987) to communicating intent (Cohen, Morgan, & Pollack, 1992) to understanding and predicting intentional actions (Dennett, 1989). Indeed Bratman (1987, p. 1) begins his influential work on practical reasoning with:

"Much of our understanding of ourselves and others is rooted in a commonsense psychological framework, one that sees intention as central. Within this framework we use intention to characterise both people's actions and their minds ... these characterizations provide a basis for our everyday attempts to predict what others will do, explain what they have done and coordinate our projects with theirs."

Thus, as noted by Han (2013), undoubtedly, intent ought to be accounted for when studying or modelling social behaviours. That said, when studying or modelling intent, two main distinctions should be made clear—ascribing intent and describing intent (Heinze, 2004). The following will describe these two in more detail before moving on to modelling intent.

Ascribing intent

Ascribing intent entails the capability of recognizing (Han, 2013) or the process of becoming aware of (Heinze, 2004) others’ intent utilizing a model. In this, it has been shown that people often utilize a folk-psychological (or common-sense) model to explain and judge others' behaviours (Malle, 1999; Malle & Knobe, 1997), and is often addressed in ‘Theory of Mind’ or mentalizing contexts (Frith & Frith, 2006). In this way, people adopt an intentional stance towards others as a strategy to judge and explain their behaviour by populating the model of others with reasonable beliefs and desires granted their context and purpose to understand and predict their behaviours (Dennett, 1989). This strategy is crucial for navigating the social world (Dennett, 1989), particularly as it enables people to reason about and adapt to others’ behaviours under communication constraints (Heinze, 2004).
The capability to recognise intent has been shown to emerge during infancy (Woodward, Sommerville, Gerson, Henderson, & Buresh, 2009) but can also be found in other species (Tomasello, Carpenter, Call, Behne, & Moll, 2005), and has been argued to be a foundation for the evolution of cooperation (Han, 2013). From a hybrid teaming perspective, it has also been shown that humans often ascribe mental states to embedded or embodied synthetic agents under certain conditions to understand and predict their behaviours (Marchesi et al., 2019; Thellman, Silvervarg, & Ziemke, 2017) particularly under conditions when interactions are framed as collaborative (Abubshait, Perez-Osorio, Tommaso, & Wykowska, 2021). This strategy to recognise and become aware of intent by collaboratively framing interactions is also something synthetic agents should have in social settings (Scassellati, 2002), particularly for fluent and effective teamwork (Tabrez, Luebbers, & Hayes, 2020), thus motivating the development of intent-aware systems that can account for and adapt to human agency. However, to enable such intent-aware systems, intent must first be described.

Describing intent

Describing intent entails the analysis of agents’ generation, representation, and execution of intent (Heinze, 2004), which, from an ascription perspective, should explain why intent is formed, what they comprise, and how they are to be enacted. This begs the question of what aspects and elements of intent ought to be described for recognising and becoming aware of intent.

To begin answering why intent is formed, the simplest answer to this is that they are responses to (anticipated) situated beliefs and desires within a context (Han, 2013; Heinze, 2004). Indeed, context is also accounted for in the intentional stance strategy (Dennett, 1989) and implicated in Hollnagel’s (2002) question of whether cognition can be context-free in the first place. Thus, in any attempt to describe intent, one must, at least to some degree, account for the context. To begin answering what intent comprises, there is no simple answer since researchers conceptualize the notion of intent differently, making it difficult to understand and predict how it will be enacted. For instance, Söderlund (2002) identified three conceptualisations of intent—intent as expectation, intent as plan, and intent as purpose. The intent concept has also been described as goals (Sukthankar et al., 2014), a combination of desires and beliefs (Davidson,
1963), and ‘choices with commitment’ (Cohen & Levesque, 1990). That said, when describing intent, albeit difficult, it should be possible to explain why intent is formed, what it comprises, and how it is enacted, which is the activity of modelling intent.

Modelling intent

Several artificial intelligence communities focus their research on how synthetic agents can effectively and fluently interact with humans, in which models play a central role in synthetic agents’ ability to reason about human behaviour (Albrecht & Stone, 2018). For instance, artificial intelligence communities are engaged in research on intent, plan, and activity recognition (Freedman & Zilberstein, 2019; Sukthankar et al., 2014; Van-Horenbeke & Peer, 2021). In this regard, it is noteworthy that artificial intelligence communities generally treat intent recognition synonymously with goal recognition (Sukthankar et al., 2014); however, it can also be understood as the capability to identify the underlying motivation behind doing something (Freedman & Zilberstein, 2019; Van-Horenbeke & Peer, 2021). In contrast, plan recognition and activity recognition concern the ability to recognise or become aware of what an agent is doing overall to achieve a goal through (a sequence of) actions and the actions themselves. Thus, in general terms, intent, plan, and activity recognition serve a complementary view of why, what, and how intent is (to be) enacted.

It has also been noted that these communities have branched into various specialized areas, focusing on different levels of analysis and challenges with few interactions and possible missed opportunities. This has, in turn, motivated proponents to argue for a more unifying perspective (Freedman & Zilberstein, 2019) and more holistic approaches (Hiatt et al., 2017; Van-Horenbeke & Peer, 2021) that accounts for both the human and artificial intelligence elements in teams (Zhang et al., 2021). However, despite these arguments for more holistic approaches, the tendency to rely on specific artificial intelligence techniques prevails, thus possibly missing the opportunities that can be gained from human factors methods.

That said, there are a few examples where human factors methods have been suggested. For instance, Cognitive Task Analysis (2009) and Cognitive Work Analysis (Lui & Watson, 2002) have been suggested to gain insights into experts’ reasoning to populate agent-based models.
Besides modelling intent to design agent-based models, techniques based on Cognitive Work Analysis have been suggested for modelling intentional systems (Elliott, Crawford, Watson, & Sanderson, 2000) and intent specification (Leveson, 2000).
Chapter III
Understanding the domain

This chapter briefly describes the domain in which this work takes place, serving to provide a better understanding of its future applications. The chapter begins by describing the context of operations before moving on to the combat aircraft domain.

The context of operations

The function of the military is to bring about the society’s intent within the boundaries (e.g. laws, edicts and orders) set by governments; often in situations that are ambiguous, ill-defined, and uncertain (Pigeau & McCann, 2006). For instance, fighter pilots operate in highly dynamic environments, in which decisions with high stakes may be necessary to be made under time pressure in ambiguous situations with conflicting goals and uncertain outcomes. In these situations, Command and Control and Commander’s intent play crucial roles by guiding operations to be in congruency with society's expectations (Pigeau & McCann, 2000, 2006).

Command and Control

According to Pigeau and McCann (2000, 2006), the Command and Control concept refers to establishing common intent for achieving coordinated actions. In this conceptualisation, Command refers to the human’s authority and responsibility expressed through creativity for achieving missions, while Control refers to the applications of structures and processes to constrain the mission's solution space. Thus, the purpose of the Command and Control concept is to balance team autonomy to cope with unanticipated events, with structures and processes bounding the solution space to maintain common intent.

Common intent

In the Command and Control concept, a key aspect is the notion of intent, which is described as the aim or purpose along with all of its associated connotations for achieving coordinated actions. In this conceptualisation, Pigeau and McCann (2000, 2006) note there is an explicit and an implicit
portion of intent, where the first is (verbally or textually) communicated, whereas the latter is uncommunicated or non-communicable.

In this regard, it has also been noted that a balance of what is to be communicated is important for establishing common intent (Klein, 1994, 1999; Pigeau & McCann, 2000, 2006). For instance, Pigeau and McCann (2000, 2006) suggested that common intent can be established by sharing intent through communication, socialization, internalization, and externalization processes. Focusing on communications, Klein (1994, 1999), on the other hand, suggested seven slots to be considered to make intent explainable and foster coordinated actions: Purpose of the mission, Mission objective, Plan sequence, Rationale for the plan, Key decisions, Anti-goals, and Constraints and considerations. Indeed, these have also been used in a Command and Control context as a model interpretive by humans and machines (Gustavsson, Hieb, Moore, Eriksson, & Niklasson, 2011).

The combat aircraft domain

Looking at three different time horizons in aviation, Jordan (2021) describes a transition from manned platforms to unmanned platforms in which hybrid teaming will take the centre stage. In the following, this structure is followed, beginning with Manned aircraft before moving to Unmanned aircraft and Manned-Unmanned Teaming.

Manned aircraft

Manned aircraft has been the predominant air combat system since world war I (Jordan, 2021), in which fighter pilots often work as teams in demanding and challenging missions (Ohlander, Alfredson, Riveiro, & Falkman, 2019). To achieve the mission, according to Shulte’s (2002) model, fighter pilots have three concurrent, and sometimes conflicting, abstract goals (Flight safety, Combat survival, and Mission accomplishment), which require several tasks to be coordinated. For instance, Anderson and colleagues (2018) described five tasks which may require prioritisation and coordination: Aviate, Navigate, Communicate, Manage, and Command decision. Additionally, whilst coordinating these tasks, the fighter pilot must also operate within the acceptable solution space described by the Commander’s intent, which may involve being at a position within a ten seconds margin, which is remarkably precise in the
context of a mission (Amalberti & Deblon, 1992). Albeit a brief overfly of the domain, it hints at some of the demands and challenges fighter pilots may face.

**Unmanned aircraft**

Unmanned aircraft have been around since 1917 (Hobbs & Lyall, 2016) but have gained more developmental momentum in the last two decades to reduce some of the demands and challenges fighter pilots face (Jordan, 2021), particularly since they are suitable for dull, dirty, and dangerous tasks (Gupta, Ghonge, & Jawandhiya, 2013). To emphasise that unmanned aircraft is only one component in missions, the notion of an unmanned aircraft system is often used. Albeit the unmanned aircraft systems may vary depending on the mission, the essential elements include one or more: human operator, control station, data link, and unmanned aircraft. Each of these elements has its own challenges in unmanned aircraft systems. For instance, since the human operator, which in a sense act as a pilot, is located elsewhere, there is a lack of cues which would otherwise be present, thus reducing situation awareness and a need for better control station interfaces (Hobbs & Lyall, 2016). Additionally, the data links allowing Command and Control of the unmanned aircraft through the control stations are susceptible to numerous factors (Meyer & Schulte, 2020), making the pilot reliant on the unmanned aircraft autonomy (Stansbury, Vyas, & Wilson, 2009). Such unmanned aircraft autonomy must also be developed for applications (Kendoul, 2013) while ensuring the pilot and unmanned aircraft can understand each other’s situation and intent.

**Manned-Unmanned Teaming**

In military aviation, the Manned-Unmanned Teaming concept was first investigated in the late 1990s (Taylor & Turpin, 2015), envisioning taking advantage of the emergent effects of combining manned and unmanned (sea, ground, air) platforms. Indeed, in its roadmap designing its vision of future unmanned aircraft systems, the Department of Defence (2014) expected to combine the inherent strength of unmanned aircraft systems with manned platforms, with synergies not seen in a single platform. Following this trend, unmanned aircraft have become the prime candidate for teaming with manned aircraft (Jordan, 2021; Sadraey, 2018). Such Manned-Unmanned Teaming envisions, like hybrid teaming, both
substituting fighter pilots for dangerous tasks or when they are unavailable (e.g. limited resources) as well as taking advantage of the emergent effects expected from combining their inherent strengths. In this regard, it is important to recognise that the mere availability of technologies does not suffice to realise Manned-Unmanned Teaming (Jordan, 2021). Indeed, it may be useful to think about Manned-Unmanned Teaming more in terms of what a team actually is. In this regard, while there are limited definitions, by lending the team concept, it can be understood as:

“A process in which a distinguishable set of fighter pilots and synthetic wingmen, who each has been assigned specific roles, interact dynamically, interdependently, and adaptively towards a common and valued goal during a mission.”

During such Manned-Unmanned Teaming missions, a fighter pilot is expected to take the role of a leader responsible for general planning and monitoring from the manned aircraft (Jordan, 2021). In contrast, the synthetic wingman is expected to be responsible for executing orders via the unmanned aircraft platform. That said, there are, of course, numerous challenges. As an instantiation of hybrid teaming, some of these challenges and how they are addressed are similar. For instance, situation awareness and workload challenges have been suggested to be addressed through transparency and control methods (Roth, Schulte, Schmitt, & Brand, 2020; Schmitt & Schulte, 2016). However, there are also differences between Manned-Unmanned Teaming and the typical hybrid teaming situation. For instance, Command and Control communication relies on data link availability—and, if communication is constrained—on the synthetic wingman’s autonomy (Jordan, 2021; Stansbury et al., 2009). This also has consequences on entrusting lethal capabilities to synthetic wingmen (Warren & Hillas, 2020), particularly when communications are constrained, thus motivating the development of intent-aware synthetic wingmen.
Chapter IV
Methodology

This chapter presents an overview of the methodological approach, with considerations and motivations for the methods used to address the research questions. The methodological approach will be described in more detail under the following sections: General approach, Designing scenarios, Defining and operationalising intent, Exploring approaches to model intent, and Model to learn and learn from models.

General approach

The approach to address the research questions in this thesis included several aspects and steps to consider, each building on the other. First, to address RQ1, a literature review related to frameworks and models of intent was conducted to define and operationalise the concept of intent. Second, to address RQ2, human factors approaches were explored to design, analyse, and evaluate models of fighter pilot intent from a human-centric perspective. Third, to address RQ3, insights gained from RQ1 and RQ2 were gathered and described, focusing on methodological recommendations for modelling intent from a human-centric perspective and design considerations for future Manned-Unmanned Teaming. However, before describing these in more detail, considerations related to designing scenarios are described since these have been used as context in this work.

Designing scenarios

The scenario concept has been described as “hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision-points” (Kahn & Wiener, 1967, p. 6). Scenarios are often presented as stories describing envisioned futures to explore what can (or will) happen and how to transition from here to there (Bishop, Hines, & Collins, 2007; Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006). As such, scenarios can provide preparedness for future possibilities and the means to manage these. Since the purpose and aim of this thesis concern modelling fighter pilot intent from a human-centric perspective in envisioned Manned-Unmanned Teaming situations, scenarios...
were used as a context to focus attention on causal and deliberative processes and means to foster preparedness for future challenges in the domain. Such preparedness is important in the early stages of development since it can drive the design of future combat aircraft systems.

There are numerous methods and techniques for designing various types of scenarios (Bishop et al., 2007; Börjeson et al., 2006). In this work, a scenario was iteratively designed in collaboration with experts, thus characteristic of a judgement technique. Such a scenario technique relies on how individuals (or groups) believe the future could (or should) be without much methodological consideration; however, it is supported by information, analogies, and reasoning (Bishop et al., 2007). The designed scenarios were characteristic of an explorative type, aiming to answer what can happen granted possible situations or developments. Such explorative scenarios are especially suitable for long time horizons and often take a starting point in the future (Börjeson et al., 2006).

In this work, scenario contexts occurring around 2035 in a national state between peace and war were designed. The scenarios were described as stories surrounding a reconnaissance mission involving Manned-Unmanned Teaming, which is both relevant and sufficiently complex in the domain (Theissing & Schulte, 2013). After identifying data link availability as a particular challenge in future Manned-Unmanned Teaming, this became a focal point when designing scenarios and modelling intent from a human-centric perspective. For instance, data links are susceptible to numerous factors (Meyer & Schulte, 2020), in which Command and Control rely on synthetic wingmen autonomy when communication is not permissible, available, or achievable (Stansbury et al., 2009). Thus, the designed scenarios in this thesis exemplify relevant challenges in future Manned-Unmanned Teaming applications, particularly addressing cases where awareness of intent is necessary with little or no communication.

**Defining and operationalising intent**

Addressing RQ1 by defining and operationalising concepts is crucial in research since this can determine the success and failure of theories and methodologies (Caws, 1959; Hollnagel, 2002). For instance, definitions are theoretical tools and pragmatic elements during analysis, making it essential to describe their meaning for clarity among researchers and practitioners (Caws, 1959). Indeed, definitions and operationalisations of
intent, or the lack thereof, may explain incongruent results in research (Söderlund, 2002).

When initiating research, one must start by becoming sufficiently confident in understanding the domain, which often involves reading and analysing texts (Hoffman, Shadbolt, Burton, & Klein, 1995). For this reason, a literature review of frameworks and models was used to define and operationalise intent in terms of its nature, functional roles and content. The definition is highly influenced by Bratman’s (1987) theory of practical reasoning. While there are other definitions of intent (e.g. Pigeau & McCann, 2006), these are rarely clear nor useful during analysis. Additionally, Bratman's theory of practical reasoning has been immensely influential in artificial intelligence communities and thus already has a well-founded connection between theory and practice (Rao & Georgeff, 1995; Silva, Meneguzzi, & Logan, 2020). The operationalisation of intent is, besides the definition, based on the Joint Control Framework (Lundberg & Johansson, 2021), Work Domain Analysis (Naikar, 2013), and earlier descriptions of intent models. That said, there are, of course, other examples for operationalising intent (e.g. Schneider & Miller, 2018), each having its purpose.

**Exploring approaches to model intent**

When addressing RQ2 by exploring approaches to design, analyse, and evaluate models of fighter pilot intent from a human-centric perspective, these approaches should be available, usable, and used in practice (Shorrock & Williams, 2016). Considering the nature of the domain and research aim in this work, approaches such as Cognitive Task Analysis (Crandall, Klein, & Hoffman, 2006), Cognitive Work Analysis (Vicente, 1999), and the Joint Control Framework (Lundberg & Johansson, 2021) were assumed to meet these criteria and used as a starting point.

When modelling intent from a human-centric perspective, whatever approach is used, the models must be populated with domain-specific knowledge (Norling, 2009). To this end, there are three main aspects and phases to consider and follow: Knowledge acquisition, Knowledge encoding, and Knowledge representation. In the following, these three aspects and phases, related considerations, and motivations in this work are described in more detail.
Knowledge acquisition

Knowledge acquisition here involves obtaining knowledge in which intent is implicated. Knowledge acquisition methods can be exemplified by interview, self-report, observation, textual, and psychometric methods (Crandall et al., 2006). For instance, an approach based on Cognitive Task Analysis methods with interviews and observations has been suggested for eliciting and capturing experts’ reasoning processes when modelling human behaviour (Norling, 2009). Similarly, interview techniques based on Cognitive Work Analysis have been suggested for eliciting expert knowledge when modelling intentional systems (Elliott et al., 2000). In this regard, it is noteworthy that Cognitive Task Analysis and Cognitive Work Analysis focus on experts’ reasoning processes and the constraints that shape how they work respectively (Hoffman & Lintern, 2006). Considering these two complementary approaches, these were also used to obtain knowledge in which intent is implicated in this work, primarily through literature reviews and subject matter expert interviews.

Literature reviews

As was noted earlier, reading and analysing text is often needed to become sufficiently confident in understanding the domain (Hoffman et al., 1995) and is useful for the early stages of modelling, when the analyst has limited knowledge about the system, with subject matter experts helping to extend and refine the preliminary model (Naikar, 2013). This strategy was also used in Paper I and Paper II, as it provided a means to understand the domain and design preliminary intent models, which were later refined and extended by knowledge from subject matter expert interviews.

Subject matter expert interviews

Subject matter expert interviews are common for acquiring knowledge, in which the Critical Decision Method is often used to obtain experts’ perspectives on experiences (Crandall et al., 2006). Additionally, interviews have been argued to be particularly suitable since participants often express themselves in mentalistic terms (e.g. beliefs and desires) to explain intent, which is practical since it is often easy to understand, encode, and map to the model (Norling, 2009).
To support the elicitation of knowledge in which intent is implicated, Study 1 utilises a strategy resembling the approach suggested by Norling (2009), where probes based on Critical Decision Method (O’Hare, Wiggins, Williams, & Wong, 1998) and Applied Cognitive Task Analysis (Militello & Hutton, 1998) were used during subject matter expert interviews. In contrast, Study 2 utilised a strategy resembling what was suggested by Elliott and colleagues (2000), in which probes associated which the different levels of cognitive control were used during subject matter expert interviews.

**Knowledge encoding**

Knowledge encoding involves exploring and discovering the most important knowledge in which intent is implicated as well as structuring and organising this content in preparation for knowledge representation. In this regard, thematic and content analysis are two common examples of knowledge encoding methods (Braun & Clarke, 2006; Harwood & Garry, 2003). Although a loosely demarcated method, thematic analysis is flexible since decisions on how to apply the method are much up to the analyst’s discretion (Braun & Clarke, 2006). For instance, whether themes and patterns should be identified through a theoretic (top-down) or inductive (bottom-up) approach, what should be a theme or pattern, and the richness of detail described.

Considering this flexibility, a theory-driven thematic analysis has been the strategy of choice, in which themes and patterns were identified to structure, identify, and discover the meaning in which intent were implicated from interview and textual data.

**Knowledge representation**

Knowledge representation concerns the design, analysis, and evaluation of intent models and is the focal point when addressing RQ2. Albeit there are numerous knowledge representation methods (Crandall et al., 2006), Cognitive Work Analysis and Joint Control Framework were used as a starting point when exploring approaches in this work. It is also noteworthy that Cognitive Work Analysis, more specifically, the Work Domain Analysis, has been used to specify intent in requirements analysis (Leveson, 2000) and represent strategic decision-making (Hoffman & Lintern, 2006).
Model to learn and learn from models

To address RQ3, the author of this thesis adopted a research stance positing that one can learn more from designing and manipulating models than from looking at them (Morgan & Morrison, 1999). This is also a strategy adopted by Research through Design proponents, noting that knowledge can be gained from the design process itself. The Research through Design strategy has been stated to have several benefits (Zimmerman, Forlizzi, & Evenson, 2007). For instance, opportunities to identify new technologies that will have a significant impact in the world, thus motivating and inspiring the development of these technologies as well as help identify gaps in theory and models. Design artefacts can also help discover unanticipated effects, providing a map to bridge aspects of a theory to a specific context and problem space. It has been argued that the contributions of the Research through Design should be evaluated based on the process, innovation, relevance and extensibility. Additionally, as was noted earlier, the approaches should be available, usable, and used in practice (Shorrock & Williams, 2016). Consequently, these criteria have been considered throughout this work as methodological and design contributions.
Chapter V
Summary of papers

This chapter begins by describing the author’s contribution to the included papers in this compilation thesis, followed by summaries of these papers. Each summary briefly describes the motivation, method, conclusions, and main contributions.

Author contribution

Table 1 provides an overview of how the author of this thesis has contributed to each paper included in this compilation thesis in terms of Planning (conception and design), Conducting (data collection and analysis), and Writing (drafting and editing).

Table 1. An overview of author contributions to the included papers in this compilation thesis.

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<th>Paper</th>
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Paper I

Paper I addresses conceptual and methodological uncertainties for modelling intent in the context of Human-Autonomy Teaming. More specifically, it identified problems related to what is supposed to be modelled to make intent explainable and how this can practically be done from a human-centric perspective. These problems motivated the aim to define and operationalise the concept as well as to explore approaches to design, analyse and evaluate models of human intent.

Method

Several theoretical frameworks and models were used to define and operationalise intent in terms of its nature, functional roles, and content;
thus providing a means to understand what aspects and elements of intent should be considered when modelling intent. Recognising the nature, functional roles, and content of intent as well as the domain of investigation, Work Domain Analysis with six levels of cognitive control was suggested as a basis for designing, analysing and evaluating models of situated intent from a human-centric perspective.

To demonstrate the usefulness of the definition, operationalisation, and Work Domain Analysis as a basis to model intent, research in the Manned-Unmanned Teaming domain (see also Paper II) was used to design and analyse a fighter pilot’s intent model.

Conclusions

The concept of intent was defined as “a structure comprised of choices characterised by commitment, with the functional roles of coordinating and guiding cognitive and physical activities personally and socially”. The definition demonstrated that intent, as a “commitment to choices”, provided practical means to distinguish it from other mental states, such as desires, thus reducing conceptual ambiguity. Additionally, the concept was operationalised as “deliberated and connotated choices connected by context-situation and means-end reasoning within an intent space with six levels of cognitive control.” The operationalisation of intent demonstrated that context-situation separation and the six levels of cognitive control provided practical means to identify and distinguish different aspects and elements of intent. Furthermore, mapping context-situation and means-end relations between decisions were argued to provide explanatory power, which was something that the reviewed intent models lacked.

Besides demonstrating the usefulness of the definition, operationalisation, and approach, methodological recommendations were also identified and described. Among these was the importance of eliciting and capturing implicit (or connotated) intent that is not readily communicated during interviews. Eliciting and capturing the reasoning behind intent was also emphasised, as these may explain how commitments to choices relate. Furthermore, recognising that prior commitments to choices may be revoked and revised, investigating the strength of such commitments and their conditions for change was recommended. Additionally, although the context was noted to be crucial when modelling situated intent, it was recommended that contextual elements should be limited to that which affects the situation.
Main contributions

Paper I is mainly a theoretical and methodological contribution addressing RQ1, RQ2, and RQ3.

- **Defining and operationalising intent** are directly related to RQ1, contributing to an understanding of what aspects and elements of intent researchers and practitioners should consider when modelling intent from a human-centric perspective.
- **Work Domain Analysis** as a basis to model intent addresses RQ2, contributing with a novel approach to model situated intent with a sound theoretical basis.
- **Methodological recommendations** concern RQ3 and seek to provide practical contributions by highlighting aspects that should be considered when modelling intent.

Paper II

Paper II primarily addresses methodological and empirical research gaps related to intent models in the context of Manned-Unmanned Teaming. More precisely, it identified a gap related to descriptions of the process of designing intent models as well as the models themselves, thus motivating such descriptions. Taking the perspective that one can model to learn and learn from models, the paper aimed to describe how intent could be modelled based on the approach described in Paper I, the designed intent models, and design considerations for future Manned-Unmanned Teaming.

Method

Through a literature review and subject matter expert interviews, Work Domain Analysis with six levels of cognitive control was used to design, analyse, and evaluate intent models. More specifically, nine work domain models related to unmanned aircraft from a literature review and seven subject matter expert interviews in the context of a reference scenario involving Manned-Unmanned Teaming were used to design two separate work domain models. These work domain models were then evaluated through comparison and synthesised into a generic intent model representing fighter pilots’ intent in the reference scenario. Additionally, by
mapping decision trajectories from interview data to the generic intent model, intent models representing fighter pilots’ intent in transfer of control and link loss situations were designed and analysed.

Conclusions

Results show that the Work Domain Analysis approach was both practical and applicable, especially as it provided formative models that are reusable and scalable; thus can be applied as a basis to inform intent models for similar situations. This notion was demonstrated by using a generic intent model as a context when designing and analysing the target transfer of control and link loss situations. Additionally, visually representing decision trajectories using the six levels of cognitive control was helpful when analysing the why, what, and how of intentional actions.

A generic intent model was synthesized by comparing and integrating information from a literature review and subject matter expert interviews, highlighting important differences. For instance, upholding security was identified as a core goal that includes information security, thus going beyond survivability. Additionally, compared to previous models, teaming aspects, such as team situation awareness, as well as procedures and contingency structures, were identified as important in Manned-Unmanned Teaming.

From analysing intent content and intent structures in the transfer of control and link loss situations, findings indicate that contextual intent and situational framings are crucial aspects to consider. For instance, results indicate that contextual goals can affect the framing of a situation, which in turn can propagate to other levels of cognitive control resulting in inconsistent or conflicting intent. The analysis also shows that common ground and common intent are primarily maintained through communication; however, it can also be done by considering previously communicated intent and its congruencies with observations. Results also show that previously communicated intent is used in anticipatory thinking, providing fighter pilots with preparedness for different situations that enable them to work proactively.

Based on these findings, design considerations were further provided, mainly highlighting the importance of contextual intent and situational framing; maintaining common ground and common intent; and anticipatory thinking.
Main contributions

Paper II mainly provides methodological and empirical contributions, addressing RQ2 and RQ3.

- **Demonstrating the Work Domain Analysis approach** addresses RQ2, showing how it can be both practical and applicable, especially as the approach provides reusable and scalable models and means to analyse intent content and intent structures.

- **A first-of-the-kind generic intent model** concerns RQ3, contributing important aspects and elements of intent to consider when designing for future Manned-Unmanned Teaming.

- **Design considerations** address RQ3, contributing with a set of implications for future Manned-Unmanned Teaming applications.

Paper III

Paper III addresses methodological and empirical gaps concerning how to model fighter pilots’ intent in mission-critical episodes. In particular, there is a need to understand how cross-temporal aspects of intent can be modelled from a human-centric perspective and understand fighter pilots’ intent concerning data link availability in Manned-Unmanned Teaming episodes. Thus, this paper aimed to fill these gaps by exploring two complementary approaches to model cross-temporal intent, using a case of fighter pilots’ intent concerning data link availability in a reference scenario.

Method

Ten semi-structured interviews with experienced fighter pilots were conducted in the context of a reference scenario, focusing on data link availability during a reconnaissance mission involving Manned-Unmanned Teaming. During the interviews, animated episodes were used to simulate the reference scenario, which, together with an interview protocol, served as means to elicit and capture participants’ intent.

The Joint Control Framework was used as a basis to model cross-temporal intent, focusing on episodes of intent formation and interpretation. Additionally, complementing the Joint Control Framework, an
Intent Matrix approach was used to model intent variation. This approach served two purposes. First, to represent and analyse the perceived autonomy boundaries in terms of choices characterized by descriptive and prescriptive dimensions of autonomy; and how these are coupled with perceptions and actions. Second, to represent and analyse decision trajectories within these perceived autonomy boundaries.

Conclusions

Results demonstrated how the approaches could be used to model cross-temporal intent from a human-centric perspective, bringing light upon fighter pilots’ intent in the reference scenario, methodological considerations, and implications for future Manned-Unmanned Teaming applications. The Joint Control Framework approach exposed a close relationship with well-known human factors models and concepts, showing how these are also relevant for modelling intent to gain novel insights. The Intent Matrix approach provided simple means to represent and analyse intent variations. Particularly as a means to represent and analyse how fighter pilots perceived autonomy boundaries in the scenario context; and how they tend to frame and manage these situations in the scenario context.

Findings show that situations, such as degrading or unavailable data links, must be understood in a larger context since direct and indirect causes and reasons, and any combination thereof, can better explain intent in these events. Through analysis of cross-temporal intent, it was observed that fighter pilots tend to use different strategies to form and interpret intent, often needing data and information with different time points for fusing retrospective and prospective processes into a single decision. Furthermore, findings indicate dependencies and interdependencies in and between deliberative and interpretative processes, which must be managed when coordinating intent at a team level. In this regard, it was noted that the persistence of decisions plays a crucial role as it can provide an awareness of its duration over a time horizon. When using the Intent Matrix approach to analyse intent variation, findings indicate that, although there is a perceived degree of freedom to manage the ascribed situation, the perceived autonomy boundaries may be misaligned with reality and between teammates. Additionally, although the analysis indicates common ascriptions to situations and how to manage these, it also shows
that misalignment of the perceived autonomy boundaries can result in conflicting intent.

Based on these findings, methodological and design considerations were provided. Among these are the importance of understanding the underlying causes or reasons for decisions and revealing these to team members; investigating how data and information with different time points are used in decisions and support the design for such decisions; examining the duration of decisions for supporting the coordination of intent; and expose dependencies and interdependencies as well as how autonomy boundaries change cross-temporally.

**Main contributions**

Paper III primarily provides methodological and empirical contributions relevant to RQ2 and RQ3.

- **The Joint Control Framework approach** addresses RQ2, contributing with a novel means to model cross-temporal intent with connections to well-known human factors models and concepts.
- **The Intent Matrix approach** concerns RQ2, contributing to an understanding of how intent variation can be modelled, supporting the representation and analysis of perceived autonomy boundaries and decisions within these boundaries.
- **Methodological recommendations** relate to RQ3, contributing with practical guidance for modelling intent.
- **Design considerations** concern RQ3, highlighting design implications for future Manned-Unmanned Teaming applications.
Chapter VI
Discussion
This chapter briefly describes and discusses the main contributions addressing RQ1, RQ2, and RQ3 under the subheading Defining and operationalising intent, Explored approaches, and Model to learn and learn from models.

Defining and operationalising intent

Addressing RQ1, the concept of intent was defined and operationalised to facilitate a better understanding of what should be modelled by describing its nature, functional roles, and content.

Defining intent

In Paper I, the concept of intent was defined as:

"a structure comprised of choices characterised by commitment, with the functional roles of coordinating and guiding cognitive and physical activities personally and socially."

The usefulness of understanding the nature of intent as ‘choices characterised by commitment’ was demonstrated in Paper I; however, it was equally relevant in Paper II and Paper III, especially as it provides practical means to separate it from related pro-attitudes (e.g. desires). This distinction corresponds with Bratman’s (1987) notion that people may desire something without acting upon those desires. Certainly, if intent and desire are treated synonymously, there may be little use for the intent concept in the first place. That said, desires, and other pro-attitudes, also have a place when modelling intent; for instance, as influencing pro-attitudes, they can explain the motivation of commitments. Surely, if people act, they likely desire something. That said, the relationship between these two has not been applied in this work; however, it points to the possibilities of modelling desire-intent relations.

Understanding intent as choices characterised by commitment also provides a rationale and means to gain insights regarding its functional roles in practical reasoning and action. For instance, how commitment to
choices can be coordinated to be actionable in anticipation of situations, connecting the formation and enactment of intent cross-temporally; how these commitments can constrain re-considerations, except in situations with new relevant beliefs or desires; and how they can constrain (or filter) inconsistent or conflicting choices intra and interpersonally. In Paper I-III, these functions could also be found. For instance, in Paper III, commitments were coordinated at a team level in anticipation of unavailable data links. In Paper II, the choice to uphold safety constrained (or filtered) the choice to continue the mission as planned. In this regard, the functional aspect of intent can highlight how commitments are coordinated to make them inconsistent and actionable personally and socially.

Through Paper I-III, intent, as choices characterised by commitment, were treated as decisions with a degree of persistence used in practical reasoning and actions. That said, it is important to recognise that there may be inherent differences between intent and decisions. Indeed, from an intentional point of view, decisions, here, are action-related with a cross-temporal aspect rarely described in decision theories and models. For instance, Bratman (1987) notes that intent tends to be future-directed, in which rational agents commit to actions in anticipation of events rather than deliberate and act in the situation at hand. In contrast, decision theories and models often concern rationality and decision-making strategies, treating decisions as a point in the situation at hand. For instance, although bounded rationality, such as satisficing strategies (Simon, 1955, 1956) and fast and frugal reasoning (Gigerenzer & Goldstein, 2011), have been immensely influential, they usually focus on cognitive and environmental constraints in situated decision-making. Similarly, although Klein's (2008) Recognition Primed Decision model and Rasmussen's Decision ladder (1986) described temporal aspects in the sense of decision steps, these mainly concern the detection and recognition of situations and events. The value of considering cross-temporal aspects of decisions becomes apparent when considering how decisions are made not only in situations—but also in anticipation of situations. That said, this is not a criticism of decision theories and models—but rather an observation that should be considered when making sense of intent. Indeed, considering how reactive, active, and proactive intent formation are intertwined in before, during, and after situations (see Paper III), the different perspectives on decisions may complement each other, explaining how different decision strategies are used in different time horizons moving from ‘optimised’ to fast and frugal rationality (Gigerenzer, 2001).
Operationalising intent

Based on theoretical frameworks and a review of intent models, in Paper I, intent was operationalised as:

“deliberated and connotated choices connected by context-situation and means-end reasoning within an intent space with six levels of cognitive control.”

Throughout Paper I-III, the operationalisation of intent was useful as it guided attention to important aspects and elements of intent. In particular, accounting for the context-situation and means-end reasoning provided practical means for identifying, differentiating, and connecting salient contextual and situational choices at the various levels of cognitive control. For instance, in Paper II, when using the generic intent model as a context for modelling situated intent, the principle of mapping context-situation and means-end reasoning provided a means to constrain (or filter) choices. In this respect, it is important to recognise that all cognition occurs in a context (Hollnagel, 2002); however, when deciding on something, not all elements in the context are considered. In this way, context-situation and means-end reasoning can provide a useful principle to constrain intent models. Additionally, considering Bratman’s (1987) notion that there is a, although unclear, connection between mental states and actions as people intend to do things and do things intentionally, the intent structures emerging from such context-situation and means-end reasoning can provide one stepping stone to understanding this connection. Indeed, following ideas by Klein and colleagues (2007), these relations may be the main source for explaining intentional actions in terms of why, what and how.

It is also noteworthy that the operationalisation of intent in this work can provide a map for artificial intelligence communities addressing the why, what, and how intent is or will be enacted. For instance, artificial intelligence communities researching capabilities such as intent (or goal) recognition, plan recognition, and activity recognition is common in this area (Sukthankar et al., 2014); however, these communities rarely work inter-disciplinary, leading to missed opportunities (Freedman & Zilberstein, 2019; Van-Horenbeke & Peer, 2021). In this regard, the operationalisation of intent can describe a general map of how different communities relate and can complement each other’s specific techniques for a more holistic approach. Indeed, as per the six levels of cognitive
control, the operationalisation goes beyond intent, plan, and activity recognition as it also points to capabilities of recognising context, situation, values, and physical objects.

**Explored approaches**

Addressing RQ2, this section first briefly describes the explored approaches to model situated intent, cross-temporal intent, and intent variation. This is followed by comparing the explored approaches, their advantages and disadvantages, and how they can complement each other.

**Modelling situated intent**

By recognising the nature, functional roles, and content of intent, Work Domain Analysis (Naikar, 2013) with six levels of cognitive control (Lundberg & Johansson, 2021) was suggested and used as a basis to model situated intent in Paper I and Paper II. A conceptual model of situated intent is illustrated in Figure 2, where an intent structure connects commitments to choices (i.e. decisions) by context-situation and means-ends relations within an intent space.

![Figure 2. A conceptual model of situated intent, illustrating an intent structure connected by context-situation and means-end relations within an intent space.](image-url)
The Work Domain Analysis approach fits well with the formative nature of intent since it can be exhibited in numerous ways. As a formative approach, the design of the work domain models usually focuses on the constraints that shape decisions rather than decision strategies or processes (Naikar, 2013). That said, for analytical reasons, decisions that are or should be made must also be represented. Thus, in a sense, designed models are re-utilised and transformed from the traditionally formative type to a type that includes descriptive or normative characteristics. Indeed, it is in these cases that intent can be represented and analysed.

When analysing intent using the Work Domain Analysis approach, the analytical focus, throughout this work, has been on the constraints that shape intent and the intent structures that emerge from context-situation and means-end reasoning. More specifically, in Paper I, it was suggested that the approach provides means to identify common, inconsistent, conflicting and underutilised intent content and intent structures. In Paper II, such inconsistent or conflicting intent structures were also identified, explained by differences in content at the frame level, which shaped decisions at other levels of cognitive control. Thus, in this way, the Work Domain Analysis approach, especially through visualisation, provided practical means to understand the point where inconsistent and conflicting intent emerged. Besides supporting the analysis of intent, due to the formative characteristics of the models, Paper II also showed that the designed models can be re-utilised by mapping decisions to extend and constrain decisions in similar situations, thus, in a sense, providing reusable and scalable models. This characteristic of models is valuable, especially as designing work domain models often are resource-demanding.

**Modelling cross-temporal intent**

Although Work Domain Analysis suits well for modelling situated intent, it is difficult, if not impossible, to model its cross-temporal aspect. For instance, how choices are deliberated, committed, and transformed as situations unfold. For this reason, the Joint Control Framework was used to model cross-temporal intent in Paper III. Figure 3 illustrates a conceptual model of cross-temporal intent, describing a sequence of perceptual input (P), choices considered (C), decisions made (D), and actional output (A) at the six levels of cognitive control.
In contrast to the Work Domain Analysis approach, the Joint Control Framework approach mainly focuses on describing cross-temporal aspects of deliberative processes. As such, designed models tend to be of a descriptive (or normative) type since they represent deliberative processes as they are (or should be) enacted. Using the Joint Control Framework approach showed a close relationship with well-known human factors models and concepts, such as the Decision ladder (Rasmussen, 1986), the Extended control model (Hollnagel & Woods, 2005), and situation awareness (Lundberg, 2015). Since the Joint Control Framework is built on these models and concepts, this is, perhaps unsurprisingly, expected; however, it also shows the relevance of these models and concepts when modelling intent.

When analysing cross-temporal intent, the focus is on how intent is (or should be) formed, shaped, and enacted as a function of the timing of perceptions, choices, decisions, and actions at the various levels of cognitive control. For instance, in Paper III, the approach was used to model fighter pilots’ intent formation and interpretation in various episodes. Findings show how the approach can be useful for gaining insights into how fighter pilots build awareness of situations and intent as well as potential decision strategies.

**Modelling intent variation**

Using intent matrices to model intent variation emerged as a need to simplify the representation and analysis of the immense variety of how intent can be manifested in different contexts and situations. In this work, intent matrices served two purposes: Model intent variation in terms of perceived autonomy boundaries and model intent variation in terms of
decisions. In other words, how intent can vary under perceived autonomy boundaries and how it does vary within these boundaries, thus representing a formative and descriptive model. The following describes these two purposes of the Intent Matrix approach.

**Intent variation as perceived autonomy boundaries**

Modelling intent variation, as how intent can vary within perceived autonomy boundaries, was motivated by a need to represent and analyse how fighter pilots’ characterised choices in terms of descriptive and prescriptive dimensions of autonomy: and how these were coupled with perceptions (ascribed causes or reasons) and actions (change or enactment of intent). To this end, intent matrices were used as a basis to represent such perceived autonomy boundaries (see Figure 4), where potential, possible, and performable choices (the grey area) and their relation to permissibility, availability, and achievability (the white area) are visually represented.

![Figure 4](image-url)  
*Figure 4. A conceptual model representing intent variation, illustrating choices characterised by descriptive (the grey area) and prescriptive (the white area) dimensions of autonomy.*
Using intent matrices to represent and analyse how intent can vary within perceived autonomy boundaries is inspired by Ashby’s (1956) notion of variety and Bradshaw and colleagues (2004) conceptualisation of autonomy. For instance, like Ashby (1956), the approach uses matrices as a simple means to represent and analyse variety (distinguishable choices) in terms of states (perceptions; ascribed causes or reasons) and how these can be regulated (change of intent, actions). Additionally, recognising that constraints shape intent, the variety can also be characterised by a descriptive and prescriptive dimension of autonomy (Bradshaw et al., 2004), particularly potential, possible, and performable choices and their relations to permissibility, availability, and achievability. In this regard, these characteristics of choices also resemble the notion of a solution space that allows team members to cope with unanticipated situations under competency, responsibility, and authority constraints (Pigeau & McCann, 2006).

When analysing intent variation, as how intent can vary within perceived autonomy boundaries, the focus is on the choices that connect perceptions and actions, for instance, how fighter pilots ascribe causes or reasons to events and how these can be managed within the perceived descriptive and prescriptive dimensions of autonomy. Such analysis is especially useful for gaining insights regarding perceived adaptability in certain situations and whether this adaptability corresponds with reality and between individuals. For instance, Paper III identified low adaptability when ascribing tactical reasons for unavailable data links. Findings also suggested that misalignments of perceived autonomy boundaries can partly explain the emergence of inconsistent or conflicting intent.

**Intent variation as decision-trajectories**

Modelling intent variation, as decisions-trajectories within the perceived autonomy boundaries, was motivated by a need to represent and analyse how intent varies cross-temporally. To this end, the intent matrix representing how intent can vary within the perceived autonomy boundaries was re-utilised by mapping decision trajectories within these boundaries (see Figure 5).
When modelling intent variation cross-temporally, considering its inspiration from Ashby (1956), it concerns the representation and analysis of intent transformations (or changes). In this case, how intent may be formed or transformed as a function of perceived state and actions. In this regard, each decision cycle that makes up the decision trajectory may, although implicitly, also carry a bit of a framing process. For instance, by recognising that actions do not sufficiently affect the perceived state, there may be reasons for questioning the frame or re-framing the perceived state (Klein et al., 2007). Compared to the aforementioned purpose of the Intent Matrix approach, which focuses on choices, the analytical focus here is on decisions connected to perceptions and actions, more specifically, how subjects tend to ascribe causes and reasons to situations and how they intend to resolve them cross-temporally. This way, patterns of deliberative processes may emerge as a function of the framing and intended management of situations. For instance, in Paper III, analysis suggests that fighter pilots tend to ascribe degrading or unavailable data links to distance; however, within the decision cycles, a point
appeared where decisions diverged, resulting in inconsistent or conflicting, intent likely due to perceiving the autonomy boundaries differently.

**Model comparison**

The three explored approaches to model intent from a human-centric perspective, each resulting in various models with different characteristics (see Table 2). In the following, these model characteristics are described in more detail.

*Table 2. An overview of model characteristics using the explored Work Domain Analysis (WDA), Joint Control Framework (JCF) and Intent Matrices (IM) approaches.*

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>WDA</th>
<th>JCF</th>
<th>IM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model purpose and analytical focus</td>
<td>Situated intent</td>
<td>Cross-temporal intent</td>
<td>Intent variation</td>
</tr>
<tr>
<td>Model type</td>
<td>Formative</td>
<td>Descriptive</td>
<td>Formative; Descriptive</td>
</tr>
<tr>
<td>Model aspects</td>
<td>Levels of cognitive control; Context-situation separation</td>
<td>Levels of cognitive control; Time</td>
<td>Levels of cognitive control; Autonomy dimensions; Time</td>
</tr>
<tr>
<td>Model elements</td>
<td>Choices; Decisions; Context-situation and means-end relations</td>
<td>Perceptions, Choices; Decisions; Actions; Processes</td>
<td>Perceptions, Choices; Decisions; Actions: Decision trajectory</td>
</tr>
<tr>
<td>Model transformability</td>
<td>Static</td>
<td>Dynamic</td>
<td>Static; Dynamic</td>
</tr>
<tr>
<td>Advantages</td>
<td>Visual; Reusable</td>
<td>Visual; Dynamic</td>
<td>Visual; Reusable; Simple</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Static; Time-consuming</td>
<td>Time-consuming</td>
<td>Static</td>
</tr>
</tbody>
</table>
Model purpose and analytical focus
Motivating the three different explored approaches used in this work, the Work Domain Analysis, Joint Control Framework, and Intent Matrix approaches served the purposes of modelling situated intent, cross-temporal intent, and intent variation from a human-centric perspective. The three explored approaches to model intent have three related, but different, analytical focuses. Regarding the Work Domain Analysis approach, the analytical focus are on the constraints that shape situated intent and intent structures that emerge from context-situation and means-end reasoning. In contrast, the Joint Control Framework approach primarily focuses on cross-temporal aspects of the deliberative process, whereas the Intent Matrix approach concerns the perceived autonomy boundaries and the deliberative processes within these perceived constraints.

Model type
Model type is here distinguished between formative, normative, and descriptive, where the first describes what actors can do, whereas the others refer to what they should or actually do (Vicente, 1999). Approaches to design formative models typically focus on the constraints to which both Work Domain Analysis and the Intent Matrix approaches adhere. In the former case, the model represents a constrained set of choices to which fighter pilots can deliberate and commit themselves through context-situation and means-end reasoning. In the latter case, the model represents a constrained set of perceived choices characterised by descriptive and prescriptive dimensions of autonomy that can be deliberated and committed; and how these are connected to perceptions and actions.

That said, although modelling choices that can be deliberated and committed is useful, descriptive or normative models are also necessary to analyse intent. In this regard, both the Work Domain Analysis and the Intent Matrix approaches can be re-utilised as normative or descriptive models by mapping how fighter pilots should decide or are deciding. In this sense, although the models per se are formative in nature, they can be transformed into other model types for analytical purposes. In contrast, due to the vast variety of how intent can be expressed in score episodes, the model type designed through the Joint Control Framework approach is characterised by a descriptive or normative type depending on the analytical purpose.
Model aspects

Model aspects here describe the essential dimensions used to represent and analyse intent. Unsurprisingly, since the six levels of cognitive control were used to operationalise intent, these aspects of intent are also used in the explored approaches. Note that while the Work Domain Analysis and Joint Control Framework approaches explicitly use these levels, they are also implicitly used in the Intent Matrix approach. The Joint Control Framework and Intent Matrix approaches also share a time aspect in models: in the former case, as time points in deliberative processes within score episodes, and in the latter case, as decision-trajectories within perceived autonomy boundaries. However, it is noteworthy that modelling cross-temporal intent using the Joint Control Framework approach allows a precise time dimension that the Intent Matrix approach cannot easily capture.

In contrast to these approaches, the Work Domain Analysis approach highlights that intent is always situated within a context where there may be several independent or interdependent situations. Indeed, in Paper I, the notion of situations-of-situations was introduced to foster an understanding that intent is always situated within a context, which by adopting a sub-frame, can become the context for a sub-situation. The Intent Matrix approach concerns perceived autonomy boundaries, with choices and decisions characterised by descriptive and prescriptive dimensions of autonomy. That said, although the other explored approaches can also use these characteristics, they tend to be represented and analysed at the Value level of cognitive control.

Model elements

Model elements here refer to the essential parts used to represent and analyse intent. Among the explored approaches, choices considered and decisions made are common in all models. Perceptions and actions are also explicitly used in the Joint Control Framework and the Intent Matrix approaches; however, they are also implicitly used in the Work Domain Analysis approach. Particularly if understanding perceptions as informing the framing of situations and intent structures exhibiting control over actions. The Work Domain Analysis and Intent Matrix approaches also share a similarity by using context-situation and means-end reasoning and decision trajectories for analytical purposes. However, whereas the former indicates intent structures manifested for (anticipated) situations,
the latter indicates how choices within these manifested structures may form and transform to manage (unanticipated) situations. The Joint Control Framework approach explicitly uses deliberative processes when designing and analysing models of cross-temporal intent; however, is also implicitly used in the Intent Matrix approach. That said, these deliberative processes resemble and carry implications for the situations-of-situations concept. For instance, as shown in Paper III, two processes can be used to manage unknown aircraft and link loss situations in the same mission context.

Model transformability
Transformability here is distinguished between static and dynamic, where the former characterises models that cannot capture changes of intent, whereas the latter can. For instance, the Work Domain Analysis approach cannot easily capture changes in intent as situations unfold and new information becomes available. In this sense, it can only provide momentary or picture-like instances of intent. In contrast, using the Joint Control Framework to model cross-temporal intent enables the representation and analysis of how intent can be formed and transformed dynamically as a function of perceptions, choices, and actions. In this regard, an intent matrix can be both static and dynamic. The intent matrix is static in that it describes a momentary instance of potential, possible, and performable choices in terms of their permissibility, availability, and achievability; however, it does not capture changes of these choices as situations unfold. That said, the intent matrix can also be dynamic as it can capture deliberative processes within these momentary instances.

Model advantages
Throughout this work, the explored approaches have allowed visual representations of intent, such as intent structures, deliberative processes, or decision trajectories. Such visual representation has been helpful, especially for identifying inconsistent or conflicting intent. Additionally, formative type models, such as those designed by the Work Domain Analysis and Intent Matrix approaches, were practical, particularly as they could be reused and repurposed for similar situations and applications.
Among the explored approaches, Work Domain Analysis is perhaps the one that best fits the operationalisation of intent, especially as it is well suited for analysing intent structures. That said, the cross-temporal aspects of these structures can only, although implicitly, be analysed in the other two explored approaches. Indeed, in a sense, when applying the Joint Control Framework, the intent structures are, although not represented, ‘stretched out’ cross-temporarily in score episodes. This is also the main advantage of the Joint Control Framework approach, as it can provide a practical means to represent and analyse how commitments in these structures are coordinated at different time points and levels of cognitive control as a function of perceptions, choices, decisions, and actions. In this regard, the main advantage of the Intent Matrix approach is the simple means of representing such perceptions, choices, and actions: and connecting these through decision trajectories.

**Model disadvantages**

Although the Work Domain Analysis and Joint Control Framework approaches are practical and applicable for insights into situated and cross-temporal intent, they can be time-consuming, especially since they have a high learning curve.

Whereas the Work Domain Analysis and Intent Matrix approaches provide means to analyse if and when inconsistent or conflicting intent emerges, such intent variation is very difficult to represent and analyse with the Joint Control Framework approach. That said, the Work Domain Analysis and Intent Matrix approaches can afford a static–or ‘picture-like’–impression of intent. This impression is erroneous as potential, possible, and performable intent have a cross-temporal aspect in which their permissibility, availability, and achievability may vary as situations unfold.

**Complementary approaches**

With their different purposes and analytical focuses, the explored approaches are complementary since they can provide different types of knowledge in which intent is implicated. To illustrate an example, the Work Domain Analysis and Joint Control Framework approaches can complement each other by showing how manifested intent structures are transformed from start to end states. Thus, opting to use two or more approaches to model intent can bring additional insights.
When comparing the different approaches and models, despite their different purposes and analytical focuses, they also share many aspects and elements of intent. In this regard, the approaches provide opportunities to transfer information between models. For instance, choices and decisions are common elements of intent in all approaches, making complementary design and analysis of intent models more efficient. Similarly, the six levels of cognitive control are common aspects of intent in the models, thus minimising the potentially high learning curve for using the approaches and effectively mapping elements of intent between models coherently. To illustrate an example, while the Work Domain Analysis approach is applied to represent the constraints in which context-situations and means-end reasoning could be analysed, these constraints can also inform the Intent Matrix approach as a means to represent and analyse the consistencies with perceived autonomy boundaries. Thus, since these explored approaches are complementary and share many aspects and elements of intent, applying them together provides opportunities for gaining different insights efficiently when modelling intent from a human-centric perspective.

Model to learn and learn from models

By taking the perspective that one can learn from the process of designing, analysing, and evaluating intent models, this part of the thesis addresses RQ3 by highlighting methodological and design considerations.

A practitioner’s guide to model intent

This section highlights insights gained throughout this work, aiming to guide practitioners interested in applying the explored approaches. In the following, these insights are collected under the categories: Adopting a pragmatic stance, Designing scenarios, Knowledge acquisition, Knowledge encoding, and Knowledge representation.

Adopting a pragmatic stance

Through Paper I-III, three novel and complementary approaches to model intent from a human-centric perspective have been applied. Each approach was considered practical and applicable for their respective purposes and analytical focuses to gain knowledge supporting the development of intent-aware systems in future Manned-Unmanned Teaming
contexts. That said, there are important considerations when modelling intent from a human centric-perspective.

First and foremost, while the explored approaches are complementary, there may be no need to apply any combination of them—or even any at all—since the situation at hand as well as the purpose and analytical focus, ought to inform this decision. Second, by lending the quote often attributed to George Box “All models are wrong, but some are useful.” Thus, adopting a pragmatic stance to design useful models under the conditions at hand is often a better strategy than designing ‘perfect’ models. Indeed, as has been argued earlier, we do not learn much from looking at models, we learn more from building and manipulating them (Morgan & Morrison, 1999).

**Designing scenarios**

Scenarios are valuable sources since they help elicit intent in envisioned futures. Among the challenges with scenarios is the acceptance of envisioned futures, especially as experts often use the current state of affairs (e.g. laws and doctrines) as a baseline (Bishop et al., 2007; Börjeson et al., 2006). This challenge was also the case during subject matter interviews in Study 1 and Study 2, where participants sometimes desired to change parts of the scenario to make it, from their perspective, more realistic. That said, these assumptions of realism can also provide insights into how fighter pilots intend to work with synthetic wingmen, highlighting potential changes that may be necessary to reach alternative futures. Nevertheless, alternative scenario techniques and types may be beneficial when modelling intent, for instance, predictive (forecasting or what-if) scenarios which build on current trends and tend to have a shorter time horizon.

Additionally, using scenario contexts with competing situations, as in Paper III, was especially fruitful as these can provide insights into what is most important. Indeed, as suggested in Paper I, the strength and change of intent should be considered, requiring the context of intent to elicit these aspects. Thus, not only should scenarios include situations that go out of the normal (Naikar, 2013) but also situations that may need to be managed concurrently to elicit different decision strategies.
Knowledge acquisition

Knowledge acquisition is the task of obtaining information about what people intend to do, why they intend to do so, and how they intend to do it. In the following, considerations and recommendations are collected under the sub-categories Capturing constrained reasoning, Finding the shape of intent, and Probing intent.

Capturing constrained reasoning

In this work, textual and interview methods have been the main sources for obtaining information in which intent was implicated; and have involved both Work Domain Analysis and Cognitive Task Analysis. Since Work Domain Analysis and Cognitive Task Analysis focus on the constraints that shape work and experts’ reasoning processes respectively (Hoffman & Lintern, 2006), these two approaches are complementary. Consequently, they should be considered to be used together as a strategy to identify the constraints that shape intent and the intent structures emerging from context-situation and means-end reasoning.

Finding the shape of intent

Throughout this work, intent has been argued to be shaped by constraints, which merits the question—what constraints? To begin to answer this question, Paper I and Paper II used the Work Domain Analysis approach to identify constraints that shape intent. Additionally, as was noted in Paper III, the perceived autonomy boundaries may differ between individuals and reality, making it important to further consider potential incongruencies. That said, there are, of course, other constraints which should be considered when acquiring knowledge, in which other phases in the Cognitive Work Analyses framework can be useful. Additionally, it may be fruitful to consider bounded rationality (Gigerenzer & Goldstein, 2011; Simon, 1955, 1956), such as satisficing and fast and frugal strategies, to find the cognitive and environmental constraints that shape intent.

Probing intent

As argued in Paper I, the context-situation and means-end relations provide explanatory power, motivating the elicitation and capturing of experts’ reasoning that connects decisions. A similar notion was argued in Paper III, where it was noted that direct and indirect causes and reasons, and any combination thereof, can better explain considered and committed choices. Unfortunately, as was noted in Paper I, obtaining knowledge
in which intent is implicated is inherently difficult. For instance, as noted by Pigeau and McCann (2000; 2006), explicit (verbal or textual) intent may be only the tip of the iceberg, making obtaining the implicit (or connoted) intent challenging. For this reason, Paper I suggested that probes related to all levels of cognitive control ought to be used. However, experience from applying this approach in Paper III showed that participants' statements, albeit implicitly, tend to carry intent content to several, if not all, levels of cognitive control simultaneously. Thus, when probing intent, methods that can obtain intent at all levels of cognitive control by communication and externalisation should be considered; for instance, by letting experts visually represent intent structures by combining Work Domain Analysis and Concept Mapping methods.

Knowledge encoding

Knowledge encoding, here, is the process of exploring, discovering, structuring, and organising knowledge in which intent is implicated.

Throughout this work, a theory-driven thematic analysis has been used, in which the definition and operationalisation of intent guided the encoding of the obtained knowledge. While this approach was practical, encoding knowledge in which intent is implicated is challenging for the analyst. Particularly when the analyst is faced with unfamiliar terminologies (Norling, 2009) and when interpreting implicit intent, which by its nature, is not expressed publicly (Pigeau & McCann, 2000, 2006). In this regard, it may be useful to involve more analysts, particularly those with domain knowledge, in the encoding phase to understand the data better and ensure credibility. It may also be useful to consider approaches in which experts are involved in the elicitation, encoding, and representation of intent. For instance, as was suggested earlier, letting experts communicate and externalise intent structures by visual means.

Knowledge representation

Knowledge representation, here, refers to the design, analysis, and evaluation of models and has been the main focus when addressing RQ2. In the following, considerations and recommendations are collected under the sub-categories Reducing complexity, Discovering the boundaries, and Exploring strategies.
Reducing complexity

When designing intent models, it is, as was noted earlier, important to make them useful for their analytical purpose, which may require a reduction of complexity. Correspondingly, as has been noted by Heinze (2004), intent may be too complex to represent, particularly since it is situated in a context, thus often requiring a reduction of detail. That said, to reduce complexity and prevent the introduction of a Laplacean demon, it is important to acknowledge that intent is shaped by cognitive and environmental constraints (Gigerenzer & Goldstein, 2011; Simon, 1955, 1956). Consequently, not all things are considered in the manifestation of intent and thus do not warrant representation. Indeed, in Paper I, it was argued that if information in the context is not used, it is not essential in the model. Thus, when designing the models, it becomes important to, in a sense, satisfice the explainability of intent; for instance, as was discussed earlier (see Defining and operationalising intent), by considering the most common context-situation and means-end relations and taking help from bounded rationality theories.

Discovering the boundaries

Since intent has been argued to be shaped by situated constraints, modelling various types and aspects of these and how they change with unfolding situations should be considered. For instance, a lack of data or information to recognise a situation or elaborate a frame (Klein et al., 2007), or no available physical systems which make the intent structure actionable. For this reason, it may be useful to revisit the descriptive and prescriptive dimensions of autonomy (Bradshaw et al., 2004) to gain insights regarding the solution space (Pigeau & McCann, 2006). For instance, by adopting a strategy to first consider if there are potential, possible and performable choices at all levels of cognitive control to make intent actionable in the first place. Then consider whether commitments to them are permissible, available, and achievable. These considerations may help the modeller gain insights into the adaptability of Manned-Unmanned Teaming, pointing to possible resilience strategies (e.g. Lundberg & Johansson, 2015, 2019). Additionally, as was noted in Paper III, perceived autonomy boundaries may be misaligned between individuals and reality, making potential discrepancies important to consider when modelling intent.
Exploring strategies

Besides recognising and becoming aware of intent, arranging commitments have been argued to be a fundamental capability (Han, Pereira, & Santos, 2012), thus prompting the question of how people coordinate intent. Indeed, in Paper III, findings indicate that different strategies to coordinate intent depend on whether it is manifested in anticipation of situations or as a response to manage or recover from them. In this regard, considering the coordination of intent in task and teamwork processes can reveal strategies, for instance, the manifestation and possible shifts between ‘optimisation’ under constraints, satisficing, and fast and frugal strategies (Gigerenzer, 2001). Paper I and Paper III also argued for investigating various aspects of commitments, such as the strength and condition for change of intent as well as its (inter-)dependencies and time horizon. In this regard, as discussed earlier (see Defining intent), the functional roles of commitments should be considered when analysing strategies to make intent consistent and actionable personally and socially.

Designing for future Manned-Unmanned Teaming

This section highlights insights gained from applying the approaches and aims to provide design considerations for future Manned-Unmanned Teaming applications. The following insights are collected under the categories: Bi-directional communication, Bi-directional transparency, Aligning autonomy boundaries, and Coordinating commitments.

Bi-directional communication

Findings in Paper I-III show that bi-directional communication is essential for upholding shared awareness of the situation and intent in Manned-Unmanned Teaming. This notion corresponds well with current research in hybrid teaming (Chen et al., 2018; Marathe et al., 2018). In the following, Bi-directional communication is further divided into Constraining communication and Tracking intent.

Constraining communication

While bi-directional communication is important, Paper II and Paper III also indicate that degrading or unavailable data links are often both expected and accepted, implying data link availability and bi-directional communication are not always warranted. Indeed, bi-directional communication requires the capability to deliver information at the appropriate
time (Marathe et al., 2018), preferably in anticipation of events and actions (Lyons et al., 2021). Considering that intent tends to be stable and largely inertia, except in situations with new relevant information (Bratman, 1987), it is reasonable that communication can be partly constrained to such new information and the possible changes of intent thereof. Thus, as a design implication, constraining communication to such timing and information should be considered.

**Tracking intent**
To further foster a shared awareness, Paper II and Paper III indicated that observations can ‘leak’ intent, particularly by recognizing the congruencies between known and observed patterns. For instance, matching previously communicated plans, procedures, and contingency structures with observations can provide shared awareness of intent. Thus, measuring the congruencies between expected and observed patterns may help communicate intent without relying on data link availability. Naturally, this pattern matching is what many artificial intelligence communities attempt to enable through observations (Sukthankar et al., 2014; Van-Horenbeke & Peer, 2021); however, it also points to the importance of complementing these techniques with information from previous communications of intent. Indeed, if one is already aware of intent, the problem can, in a sense, be reduced to tracking intent (Howard & Cambria, 2013).

**Bi-directional transparency**
In the context of Manned-Unmanned Teaming, bi-directional (or teamwork) transparency can be understood as the process of fighter pilots and synthetic wingmen upholding shared awareness of the situation and intent (Chen et al., 2018; Lyons, 2013). Thus, it is closely related to bi-directional communication but does not rely on verbal or textual interactions (Schelble et al., 2020). In the following, bi-directional transparency is further divided into Information tailoring, Making relations salient, and Framing the situation.

**Information tailoring**
Like communication, information needs tailoring (e.g. type, amount, time) to the situation (Chen et al., 2018; Lyons & Havig, 2014). In this regard, frames, as described in Paper I, can provide a rationale for separating the situation from its context, helping to filter the type and amount
of information used to establish shared situation awareness. Additionally, like bi-directional communication, information should be tailored to explain intent (Klein, 1994), for instance, by utilising the six levels of cognitive control used to model intent. Thus, the six levels of cognitive control may provide a foundation for tailoring shared awareness of situation and intent in future Manned-Unmanned Teaming contexts.

Making relations salient
Corresponding with transparency models (Chen et al., 2018; Lyons, 2013), as pointed out in Paper II and Paper III, contextual and situational causes and reasons ought to be transparent for team members to understand the motivation for choices considered and committed. In this regard, it may also be necessary to go beyond prima facie explanations, for instance, by making the relationships within the frames transparent since these can have explanatory power (Klein et al., 2007). By the same token, to further reduce the emergence of inconsistent and conflicting intent, it may be useful to make the context-situation and means-end reasoning transparent, for instance, by making the connections between elements at the various levels of cognitive control salient, particularly if these do not correspond with expectations.

Framing the situation
Additionally, as findings indicated in Paper II, the framing of situations can shape intent. Thus, being transparent about the framing process in future Manned-Unmanned Teaming applications may facilitate shared situation awareness as well as reduce the emergence of inconsistent and conflicting intent. Indeed, as noted earlier, each decision cycle may carry a bit of framing, in which being transparent about the processes of the elaboration, questioning, and change of frames may help uphold shared awareness of the situation and intent. For instance, it may be useful to indicate what data is used to recognise a situation and its congruency with the expected situation as well as what data is missing and searched for in the context.

Aligning autonomy boundaries
As has been argued through Paper I-III, intent is situated and shaped by constraints, making it crucial to describe these situated constraints via communication and transparency methods in future Manned-Unmanned
Teaming contexts. These considerations are further discussed under *Aligning autonomy boundaries* and *Balancing autonomy boundaries*.

**Aligning autonomy boundaries**
Although fighter pilots and synthetic wingmen will likely rely on predefined plans, procedures, and contingency structures, adaptability is also necessary for unanticipated Manned-Unmanned Teaming situations. From a Command and Control perspective, this entails the establishment of common intent to achieve coordinated action within a solution space (Pigeau & McCann, 2000, 2006). For instance, Paper III showed the importance of being aware of each team member’s autonomy boundaries cross-temporally since data link availability is interdependent on how they can and should operate over different time horizons. That said, findings also indicated that the perceived autonomy boundaries might be misaligned between individuals and reality. These findings highlight the importance of using communication and transparency methods, for instance, by making the descriptive and prescriptive dimensions of autonomy (Bradshaw et al., 2004) salient cross-temporally to maintain common intent and achieve coordinated action.

**Balancing autonomy boundaries**
Besides being aware of the autonomy boundaries, these may also need to be balanced for resilient Manned-Unmanned Teaming (Pigeau & McCann, 2000, 2006). For instance, as was noted in Paper III, there may be causes or reasons which inhibit resilience strategies since it reduces control possibilities. However, that said, maximising adaptability, quite counter-intuitively, may also inhibit resilience strategies since it reduces anticipation capabilities. Thus, in a Manned-Unmanned Teaming context, it becomes important to be able to balance autonomy boundaries cross-temporally to maintain common intent and resilience capabilities over time.

**Coordinating commitments**
As was discussed earlier, coordinating commitments is a fundamental capability for task and teamwork (Han & Pereira, 2013), thus should be considered when designing for future Manned-Unmanned Teaming applications. In the following, these design considerations are discussed under the sub-categories *Decision point, Decision duration,* and *Decision compatibility.*
**Decision point**

Albeit coordinating intent in deliberative processes is crucial, it also comes the point in time when commitments must be made in this deliberative process (Bratman, 1987). In this regard, findings in Paper III highlight the importance of supporting both retrospective and prospective processes to support situation awareness; and the need to fuse these into a single decision point when coordinating intent. Although this has been suggested earlier (Chen et al., 2018), it has mainly concerned performance (e.g. errors) and expected outcomes; however, there may be other types of information that are crucial for coordinating effective and fluent Manned-Unmanned Teaming.

**Decision duration**

Throughout this work, intent has been argued to be choices characterised by commitment, implying that these commitments have a duration. Indeed, although intent may have a time point for coordinating actions (Schneider & Miller, 2018), it is also important to recognise that decisions have a duration of applicability. For instance, findings in Paper III show that there may be a need for coordinating commitments with different durations. For instance, to know when a previous commitment to a plan is no longer applicable and should be changed to a contingency structure. Consequently, fostering the sharing of the time horizons of commitments through communication and transparency methods can support the coordination of actions in Manned-Unmanned Teaming applications.

**Decision compatibility**

When coordinating intent, it becomes essential to consider dependencies and interdependencies within the perceived autonomy boundaries over different time horizons to support resilient Manned-Unmanned Teaming. For instance, findings in Paper III showed that data link availability is interdependent on how the fighter pilot and synthetic wingman operate; however, also that unavailable data links are often both expected and accepted within their perceived autonomy boundaries. Thus, to further support the coordination of actions in future Manned-Unmanned Teaming, it becomes important to consider how commitments can be coordinated within these perceived autonomy boundaries; for instance, by making permissible, available, and achievable choices—and their compatibility with other decisions—salient.
Limitations

Throughout this work, some limitations should be highlighted. First, a general limitation regarding the designed intent models is that they rely on text and interview data. While the interviews were conducted with reference scenarios as a context, text and interview data can only capture espoused theories rather than theories in action (Argyris & Schön, 1974). Thus, what participants said they intended in the reference scenario may not correspond with what they would intend in a real setting, potentially threatening ecological validity. In this regard, complementary approaches are necessary, preferably ones that can sufficiently make the connections between mental states and observable actions.

A second limitation relates to the number and representativeness of participants. For instance, in the two studies making up the included paper in this compilation thesis, a total of 17 subject matter experts participated. Such a small number of participants threatens the reliability and validity of findings. Particularly since three participants (one ground control station operator and two technical specialists) in the first study, although provided complementary perspectives, cannot be said to be representative of the fighter pilot population. That said, the findings also indicate a variety within the fighter pilot population, showing a need for further studies to strengthen the credibility of the findings in this work.

Third, through this work, the author of this thesis was the main analyst, albeit support for conducting this was in collaboration with co-authors; there is a risk of misinterpretations and biases. Thus, future studies need to corroborate the findings in these studies.

Future directions

This section aims to bring the work in this thesis together, pointing to directions regarding Designing scenarios for alternative futures, Implementing models, Exploring modelling, and Designing for a shared intent space.

Designing scenarios for alternative futures

Throughout this work, cases of fighter pilots’ intent concerning data link availability have been a focal point in the designed scenarios. However, with that said, these cases merely scratch the surface of situations relevant
when modelling fighter pilot intent for the development of future Manned-Unmanned Teaming applications. Thus, future work should consider other cases of relevance when designing scenarios, possibly with other techniques and types to guide the development of envisioned futures.

Additionally, since the scenarios in this work have used low-fidelity simulations (moving objects on the surface of a paper and animations), future applications of designed scenarios should consider higher resolution fidelity, preferably with observable interactions.

**Implementing models**

To enable intent-aware systems, translating knowledge from the designed intent models to implementable models should be considered in future work. Particularly since such implementable models can validate and refine designed models as well as highlight absent and dispensable aspects and elements of intent. For instance, translating knowledge from the generic intent models described in Paper II as a basis to implement models in a simulation enables further learning from the design and manipulation of intent models for Manned-Unmanned Teaming applications.

**Exploring modelling**

This section points to the possibilities of exploring approaches involving Collaborative modelling and Complementary modelling.

**Collaborative modelling**

As discussed earlier, the analyst can find knowledge acquisition, encoding, and representation difficult. Consequently, exploring approaches in which intent models can be designed, analysed, and evaluated in collaboration with subject matter experts should be considered in future work. For instance, by inviting participants throughout the modelling process or by, as was suggested earlier, letting participants explicitly represent their intent structures in models.

**Complementary modelling**

As was noted earlier, Cognitive Work Analysis and Cognitive Task Analysis can be complementary when modelling intent from a human-centric perspective, in which other methods in these frameworks should be
explored to, in a sense, find the shape and structure of intent. In this regard, it is also important to recognise that verbal sources (textual or vocalised) can only provide the espoused models, not the model in use (Argyris & Schön, 1974), directing future work towards exploring approaches that can corroborate espoused models by models in use.

Additionally, as was discussed earlier (see Defining intent), since intent is often explained by other mental states (e.g. beliefs and desires), there are reasons to explore approaches that can model these relations. For instance, whether other decisions would be preferred and whether beliefs about choices correspond with reality.

**Designing for a shared intent space**

Albeit this work has highlighted several design considerations for future Manned-Unmanned Teaming applications, none of these has taken any form. Consequently, there is much room for design to meet the challenges in which intent is implicated; for instance, the tailoring of information used to foster shared awareness of situation and intent as well as how to align perceived autonomy boundaries and coordinated intent within these boundaries. One way forward is applying the notion of intent space to design a shared semantic space characteristic of the autonomy boundaries, allowing communication and coordination of intent (e.g. Gustavsson et al., 2011; Schneider & Miller, 2018).
Chapter VII
Conclusions
This chapter concludes this thesis by revisiting the research aim and overarching purpose of this thesis.

On the path to model intent
Aiming to support the design, analysis, and evaluation of intent models from a human-centric perspective, this work has strived to clear a path towards future intent-aware systems in a Manned-Unmanned Teaming context. To this end, the concept of intent was operationalised and defined. Thus, in a sense, placing a sign along the path that shows the direction towards what is supposed to be modelled. Additionally, three novel and complementary approaches to model human intent from a human-centric perspective were explored, illuminating possible paths to reach the destination. Through walking these paths, gained experiences were put together as a guide, supporting explorers walking in the same direction.

So, did the work reach the aim? To answer this question, one must consider whether the work provided knowledge contributions, or in other words, useful information. In this regard, information in this work has provided theoretical, methodological, and empirical contributions that can support the aim. Particularly, the definition and operationalisation of intent provided useful means to distinguish intent from related concepts as well as separate and connect different aspects and elements of intent. This is especially valuable since the concept of intent is often ambiguous in research. Three novel approaches were explored and shown to be both practical and applicable for modelling intent from a human-centric perspective, particularly as they can complement each other for different analytical purposes. These novel approaches are valuable since the process of designing, analysing, and evaluating intent models from a human-centric perspective is rarely—if ever—described in the literature. Taking the perspective that one can learn from designing, analysing, and evaluating intent models, the explored approaches also showed their value as they can contribute with theoretical, methodological, and empirical insights.
On the horizon

Considering that the purpose of this work has been to support the design of future intent-aware aircraft systems in the context of Manned-Unmanned Teaming, what can we see looking ahead?

To be crass, there will not be any intent-aware aircraft systems in the foreseeable future for the simple reason that they, like humans, cannot read minds. That said, humans have the capability to reason about what others are doing, why they are doing that, and what they will do next to coordinate in the social world. Even though they are unaware of the true intent, this capability is what intent-aware systems attempt to emulate. In this regard, this work can provide a map to artificial intelligence communities with a more holistic approach, in which the explored approaches can bring insights into what aspects and elements of intent ought to be modelled in the first place. Indeed, recognising that intent is situated and shaped by constraints also implies a strategy in which modelling the shape of intent can reduce the problem of recognising its structure. Additionally, whilst artificial intelligence communities mainly concern the capability and process to recognise and become aware of intent through observations, communication will be a large part of future Manned-Unmanned Teaming coordination.

Ultimately, this work shows that modelling intent from a human-centric perspective can bring new light upon challenges and opportunities for future Manned-Unmanned Teaming.
References


https://doi.org/10.1016/j.ress.2015.03.013


Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

https://doi.org/10.3384/9789179295486