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Mission Specification Patterns for Mobile Robots: Providing Support for Quantitative Properties

Claudio Menghi, Christos Tsigkanos, Mehrnoosh Askarpour, Patrizio Pelliccione, GriceL Vazquez, Radu Calinescu, and Sergio García



Abstract—With many applications across domains as diverse as logistics, healthcare, and agriculture, service robots are in increasingly high demand. Nevertheless, the designers of these robots often struggle with specifying their tasks in a way that is both human-understandable and sufficiently precise to enable automated verification and planning of robotic missions. Recent research has addressed this problem for the functional aspects of robotic missions through the use of *mission specification patterns*. These patterns support the definition of robotic missions involving, for instance, the patrolling of a perimeter, the avoidance of unsafe locations within an area, or reacting to specific events. Our paper introduces a catalog of *QUantitative RoboTic mission spEcificaTion patterns* (QUARTET) that tackles the complementary and equally important challenge of specifying the reliability, performance, resource use, and other key quantitative properties of robotic missions. Identified using a methodology that included the analysis of 73 research papers published in 17 leading software engineering and robotics venues between 2014–2021, our 22 QUARTET patterns are defined in a tool-supported domain-specific language. As such, QUARTET enables: (i) the precise definition of quantitative robotic-mission requirements; and (ii) the translation of these requirements into probabilistic reward computation tree logic (PRCTL), and thus their formal verification and the automated planning of robotic missions. We demonstrate the applicability of QUARTET by showing that it supports the specification of over 95% of the quantitative robotic mission requirements from a systematically selected set of recent research papers, of which 75% can be automatically translated into PRCTL for the purposes of verification through model checking and mission planning.

Index Terms—Robotics Software engineering, Robotic Missions Specification, Quantitative Properties, Domain-specific Languages, Probabilistic Reward Computation Tree Logic

1 INTRODUCTION

THE engineering of robotic applications is a complex interdisciplinary activity. Similar to many other domains, robotics requires contributions from different yet interdependent engineering roles. Robotics engineers build low-level primitives that allow higher-order control, while

software engineers develop higher-level software components executed by robots [1]. As such, there is a great need for software solutions that can support the multiple activities of the engineering process – from requirements elicitation to software development and validation, e.g., [2], [3], [4], [5], [6], [7]. Mission specification is among the most important of these activities, as it entails capturing the requirements of robotic applications in a precise manner and in a form useful for automatic processing. Mission specification touches upon – and draws from – multiple aspects of development, ranging from capturing *what the robot(s) should do* and *how it should be done* to evaluating if the resulting behavior(s) indeed *satisfy what was intended* for the mission. Due to this multifaceted role, mission specification represents one of the main challenges in engineering robotics software [8], [9].

Typically, the engineering of robotics software is bootstrapped by requirements described in natural language, which are then translated into precise *mission specifications*. Such a *mission requirement* describes the high-level tasks that a robotic application must accomplish [10]. To be accessible, this description should use a notation that is high-level and user-friendly [10], [11]. At the same time, it should preclude misinterpretation and enable the automatic verification and synthesis of the robotics software by formally and precisely specifying what the robot(s) should do in terms of movements and actions [12], [13], [14]. We use the term *mission specification problem* for the problem of (automatically) generating a mission specification from a mission requirement. The main uses of mission specifications are: (i) unambiguous communication of the mission within the engineering team developing a robotic application and to other stakeholders, (ii) verification, where the robotic software or behaviors sourced from a robotic system or its simulation are checked against the specification, and (iii) synthesis, where behaviors that provably satisfy the specification are constructed.

Mission specifications are often expressed in domain-specific languages (DSLs), many of which have been proposed over the last decades [15], [16]. These DSLs are usually integrated with development environments, enabling the generation of code that can then be executed within simulators or by real robots [17], [18], [19], [20], [21]. However, these languages are typically bound to specific types of robots, and support a limited class of missions. Moreover,

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these languages are procedural and therefore require a step-by-step specification of the precise tasks that the robots should perform.

Other research, especially from the robotics domain, advocates the use of temporal logics to formally specify missions and they enable to specify missions in a declarative way, i.e., to specify what should be achieved without expressing how this should be achieved [22], [23], [24], [25]. However, specifying missions in terms of temporal logic formulae is complex and error-prone for practitioners and engineers. As such, defining robotic missions is generally challenging, as widely recognized in both the software-engineering and robotics communities [26], [27], [28], [29]. Indeed, while precise specifications in logical languages enable reasoning [30], [31], their definition is difficult and prone to errors [32], [33]. Practitioners are often unfamiliar with the specification process and the complicated syntax and semantics of logical languages [34]. To ameliorate this, we have recently proposed a set of specification patterns for robotic missions [35], [36], [37], which provide template solutions that support users in specifying common mission concerns. Within this pattern-based approach, requirements are expressed in a domain-specific language, and then automatically translated into logic-based specifications that can be fed into existing logic-based planners and verifiers (e.g., [31], [38], [39], [40], [41], [42], [43]). However, the patterns from [35], [36], [37] target abstract robotic mission concerns – such as constraints in the ordering of robot actions or triggers – ignoring the quantitative aspects of robotic missions.

Quantitative aspects, however, are key to practical robotics applications. Users and operators of robotic systems often require behaviors that ensure quantitative constraints such as upper bounds on the *time* a robot takes to perform an action, the *energy consumption* to complete that action, or the *probability* of failing to achieve a mission goal. In this paper, we introduce a catalog of QUantitAtive RoboTic mission spEcificaTion patterns (QUARTET) that bridges this gap. QUARTET provides declarative specification [44] patterns that enable the definition of quantitative constraints and optimisation objectives for robotic missions, and supports: (i) the unambiguous specification and communication of quantitative aspects associated with robotic missions; (ii) the verification of mission plan compliance with quantitative requirements; and (iii) the synthesis of correct-by-construction mission plans that meet these requirements. Moreover, we extended our previous catalog of patterns and its DSL [35], [36], [37] instead of extending an existing one (see the reference above), since other DSLs are typically tailored to a specific target specification language, e.g., the specification language of a particular model checker, and this places boundaries on their expressiveness. A key characteristic of our patterns is that they are built from data collected from research literature. Therefore, collected data shapes both the patterns and the DSL. Our patterns are language-agnostic and can be used as main building blocks for other DSLs specialized on specific needs, as has already occurred for our previous catalog of patterns [35], [36], [37], which has been exploited to build the Promise DSL [21], [45]. These aspects are detailed in the related work section.

Our main contributions lie within the area of software engineering for robotics and are detailed below.

- We introduce a comprehensive *catalog of 22 quantitative mission specification patterns*, called QUARTET, for the definition of quantitative constraints and optimisation objectives for robotic missions. These patterns support the mission specification problems identified by using our hybrid methodology and systematically analyzing 51 quantitative robotic-mission requirements published in 17 leading software engineering and robotic venues over six years (Section 5). Our patterns focus on robot movement as one of the major aspects considered in the robotics domain [46], [47], [48], as well as on how robots perform actions as they move within their environment.
- We define a *pattern-based DSL* that supports the usage of both the existing (functional) mission specification patterns from [35] and the quantitative patterns from our QUARTET *catalog*, and a translation that maps the constructs of the QUARTET DSL to Probabilistic Reward Computation Tree Logic (PRCTL) formulae. These PRCTL formulae precisely define the semantics of our QUARTET language, enabling its use with existing model checking and synthesis tools (Section 6). The pattern-based DSL extends the DSL proposed for the (non-quantitative) robotic specification patterns we introduced in [35], [36], [37].
- We provide the QUARTET *tool* that supports the use of our pattern-based DSL, enabling engineers to (i) express complex behaviors involving quantitative concepts and (ii) directly interface with the widely used probabilistic symbolic model checker PRISM [49] (Section 7).
- We evaluate the coverage of the QUARTET pattern catalog (research question *RQ1*), the applicability of our translation (*RQ2*), and the exploitability of the logic formulae generated by our translation (*RQ3*). For *RQ1*, our results show that our quantitative patterns were able to fully express 20 out of the 21 (~95%) mission requirements of the benchmark we considered and that each pattern was useful to express at least one requirement we collected from the literature. For *RQ2*, our results show that our translation was applicable for 15 out of the 20 mission requirements expressible using our DSL (75%). For *RQ3*, our results show that the mission specifications generated by our translation can be used for synthesis and model checking, and that, based on results from the literature, these activities can be performed in practical time (Section 8).
- All of our artifacts are publicly available to allow for study replication [50].

The rest of the paper is structured as follows. Section 2 introduces a running example used to illustrate the QUARTET patterns throughout the paper. Section 3 presents preliminary background notions. Section 4 describes the hybrid methodology we used to identify mission specification problems, and the result of applying this methodology to collect requirements relevant for our work. Section 5 presents our catalog of quantitative patterns. Section 6 introduces the QUARTET DSL, which enables using and combining the 22 robotic mission specification patterns [35] and the new patterns from our QUARTET catalog. Section 7 addresses implementation specifics. Section 8 evaluates our approach. Section 9 positions our work with respect to related

203 approaches in the software engineering for robotics literature,
204 and Section 10 concludes the paper with a brief summary
205 and a discussion of future work directions.

206 2 RUNNING EXAMPLE

207 Our running example concerns a robotics company develop-
208 ing general-purpose mobile robots. After the production
209 of the robots, the engineers can customize their behaviors
210 by defining different types of missions the robots can
211 perform. These missions are defined depending on customer
212 needs. Since the company provides general-purpose robots
213 deployed in customer facilities, customers frequently ask the
214 robotic company to add, remove, or change robotic missions
215 based on their specific needs. This customization can be
216 performed on-site, or remotely after the deployment of the
217 robots.

218 For our running example, the customer is an electronics
219 store that purchased two robots (*rob1* and *rob2*) and
220 deployed them in their store. The store is organized in three
221 areas: the computer-phone (CP), the tv-audio (TA), and the
222 household appliance (HA) areas. The robots have to perform
223 the following mission:

224 **Example 1.** “After closure, the robots shall clean the electronics
225 store. After cleaning, they shall visit a set of predefined store
226 locations, each at least once, to record the items present on
227 shelves after closure. The robots must minimize the time
228 required to perform this activity. The robots should also patrol
229 the store for security purposes, following any intruder while
230 raising an alarm. The robots should interleave cleaning and
231 security patrolling so that intruders do not remain undetected
232 while the robots are cleaning continually for long periods
233 of time. The robots should monitor their battery, optimize its
234 usage, and recharge when needed. They should avoid recharging
235 simultaneously and leaving the store unmonitored.”

236 This task, or *mission requirement*, is a natural-language de-
237 scription of the activities that the robots have to perform [35].
238 Robotics engineers typically use a planner that computes
239 the set of actions the robots should perform to accomplish
240 a mission from a machine-processable description of that
241 mission, i.e., from a *mission specification*. Therefore, software
242 tools are required for (a) expressing mission requirements
243 and (b) translating mission requirements into mission speci-
244 fications.

245 3 PRELIMINARIES

246 This section summarizes the robotic mission specification
247 patterns [35] (Section 3.1), that will be extended in this work
248 to express mission requirements, and Probabilistic Reward
249 Computation Tree Logic (PRCTL) [51] (Section 3.2), the logic
250 that will be considered for expressing mission specifications.

251 3.1 Mission Specification Patterns

252 *Robotic mission specification patterns* [35] allow engineers to
253 tackle the mission specification problem. A pattern maps
254 a recurrent mission requirement (or parts of a mission
255 requirement) to a template specification. For simplifying
256 its usage, a pattern is associated with a description of the
257 usage intent, known uses, and relationships to other patterns.

258 Mission specification patterns are organized in a *mission*
259 *specification pattern catalog*: a collection of patterns organized
260 in a hierarchy aiding browsing and selecting patterns to
261 support decision making during mission specification. Given
262 a mission requirement, the 22 mission specification pat-
263 terns [35] support the automatic generation of a mission
264 specification. The mission specification is an unambiguous
265 description of the mission requirement, often expressed in a
266 logic-based or programming language that supports robotic
267 planning.

268 The (non-quantitative) patterns defined in [35] and lever-
269 aged by our complementary quantitative QUARTET patterns
270 are summarised in Table 1. The table contains the name
271 of the mission specification problem that each pattern is
272 solving and a natural language description of that problem.
273 In addition, the table contains the constructs of the DSL
274 that enable the usage of the patterns that are introduced by
275 this work, and will be described in Section 6.1. The table is
276 partitioned into three parts that respectively contain the *Core*
277 *Movement*, *Avoidance/Invariance*, and *Trigger* patterns. Core
278 movement patterns describe how robots should move within
279 their environment. Avoidance/Invariance patterns capture
280 constraints that can be added to avoid the occurrence of a
281 specific behavior. Trigger patterns express a robot reactive
282 behavior based on stimuli, or the robot’s inaction until a
283 stimulus occurs.

284 3.2 Probabilistic Reward Computation Tree Logic (PRCTL)

285 The target logic we consider in this work to express mis-
286 sion specifications is Probabilistic Reward Computation
287 Tree Logic (PRCTL) [52]. PRCTL provides support for the
288 specification of temporal properties that contain probability
289 and rewards. Let AP be a set of atomic propositions and
290 $a \in AP$, $J \subseteq \mathbb{R}_{\geq 0}$, $n \in \mathbb{N}$, $p \in [0, 1]$, $N \subseteq \mathbb{N} \cup \{\infty\}$,
291 and $\trianglelefteq \in \{<, >, \leq, \geq\}$, the syntax of a PRCTL formula ϕ
292 is defined as follows:
293

$$\phi \equiv a \mid \phi_1 \wedge \phi_2 \mid \neg\phi \mid \mathcal{L}_{\trianglelefteq p}(\phi) \mid \mathcal{P}_{\trianglelefteq p}(\phi_1 \mathcal{U}_J^N \phi_2) \mid \mathcal{P}_{\trianglelefteq p}(\mathcal{F}_J^N \phi) \mid \\ \mathcal{P}_{\trianglelefteq p}(\mathcal{G}_J^N \phi) \mid \mathcal{E}_J^n(\phi) \mid \mathcal{E}_J(\phi) \mid \mathcal{C}_J^n(\phi) \mid \mathcal{Y}_J^n(\phi)$$

294 PRCTL properties are interpreted over discrete-time
295 Markov reward models (e.g., [53]), i.e., state machines
296 containing states labelled with probabilities and rewards.
297 Informally, the semantics of the PRCTL operators is as
298 follows. The semantics of the operators $\phi_1 \wedge \phi_2$ and $\neg\phi$
299 is the classical semantics of conjunction and negation. The
300 other Boolean operators are derived as usual. The operator
301 $\phi_1 \mathcal{U}_J^N \phi_2$ asserts that (a) ϕ_2 will be satisfied within $j \in N$
302 states, and that all preceding states satisfy ϕ_1 , and (b) the
303 accumulated reward until reaching the state that satisfied
304 ϕ_2 is within the interval J . The operator $\mathcal{L}_{\trianglelefteq p}(\phi)$ asserts
305 that the average probability in the states that satisfy ϕ
306 meets the bound $\trianglelefteq p$. The operator $\mathcal{P}_{\trianglelefteq p}(\phi \mathcal{U}_J^N \phi)$ asserts that
307 the probability of the paths that satisfy $\phi \mathcal{U}_J^N \phi$ meets the
308 bound $\trianglelefteq p$. The operator $\mathcal{E}_J^n(\phi)$ asserts that the expected
309 reward rate in states satisfying ϕ after firing up to n
310 transitions lies within the interval J . The operator $\mathcal{E}_J(\phi)$
311 asserts that the expected reward rate in states satisfying
312 ϕ meets the bounds of J . The operator $\mathcal{C}_J^n(\phi)$ asserts that
313 the reward in states satisfying ϕ after firing n transitions

TABLE 1
Mission specification problems from [35] and constructs of the DSL addressing the problem.

Problem	Description	DSL
<i>Visit</i>	Visit locations in <code>locs</code> in an unspecified order	<code>visit locs</code>
<i>Sequence visit</i>	Visit locations in <code>locs</code> and visit <code>loc_{i+1}</code> after <code>loc_i</code> .	<code>visit in sequence locs</code>
<i>Ordered visit</i>	Visit locations in <code>locs</code> in sequence and do not visit <code>loc_{i+1}</code> before <code>loc_i</code> .	<code>visit in order locs</code>
<i>Strict ordered visit</i>	Visit locations in <code>locs</code> in order and avoid visiting <code>loc_i</code> more than once before <code>loc_{i+1}</code> .	<code>visit in strict order locs</code>
<i>Fair visit</i>	The difference of the number of times the locations in <code>locs</code> are visited is at most one.	<code>visit fairly locs</code>
<i>Patrolling</i>	Repetitely visiting locations in <code>locs</code> in an unspecified order.	<code>patrol locs</code>
<i>Sequence patrolling</i>	Keep visiting the locations in <code>locs</code> in sequence, one after the other.	<code>patrol in sequence locs</code>
<i>Ordered patrolling</i>	Patrol in sequence by not visiting a successor location (again) before its predecessor.	<code>patrol in order locs</code>
<i>Strict Ord. Patrolling</i>	Patrol in order by not remaining in the same location for two consecutive instants.	<code>patrol in strict order locs</code>
<i>Fair patrolling</i>	Patrol and ensure the number of times the locations are visited differs at most by one.	<code>patrol fairly locs</code>
<i>Past avoidance</i>	A condition has to be fulfilled in the past before entering a location.	<code>avoid loc until cond</code>
<i>Global avoidance</i>	Avoid entering a location.	<code>avoid loc</code>
<i>Future avoidance</i>	After the occurrence of a condition, avoidance of a location has to be fulfilled.	<code>avoid loc after cond</code>
<i>Upper Rst. Avoidance</i>	Visit <code>loc</code> less than <code>n</code> times	<code>visit less than n times loc</code>
<i>Lower Rst. Avoidance</i>	Visit <code>loc</code> more than <code>n</code> times	<code>visit more than n times loc</code>
<i>Exact Rst. Avoidance</i>	Visit <code>loc</code> exactly <code>n</code> times	<code>visit exactly n times loc</code>
<i>Inst. Reaction</i>	Applies when occurrence of a stimulus instantaneously triggers a counteraction.	<code>react instantly to cond [...]</code>
<i>Delayed Reaction</i>	Applies when the occurrence of a stimulus triggers a counteraction later.	<code>react with a delay to cond [...]</code>
<i>Prompt Reaction</i>	The occurrence of a stimulus triggers a counteraction promptly.	<code>react promptly to cond [...]</code>
<i>Bound Reaction</i>	Perform a counteraction when a condition occurs.	<code>ct. instantly to cond [...]</code>
<i>Bound Delay</i>	Perform a counteraction in the next time instant when a condition occurs.	<code>ct. with a delay to cond [...]</code>
<i>Wait</i>	Wait in a <code>loc</code> until the occurrence of <code>cond</code> .	<code>wait in loc. loc until cond</code>

* `locs` is a sequence of locations, `loc` is a location, `cond` is a condition, `n` is a positive natural number.
`ct.` and `loc.` are shortcuts for **counteract** and **location**.
 [...] represents portions of the DSL of Figure 4 omitted for graphical reasons.

314 meets the bounds of J . The operator $\mathcal{V}_J^n(\phi)$ asserts that
 315 the accumulated reward in states satisfying ϕ until the n -th
 316 transition is fired meets the bounds of J . The eventually
 317 ($\mathcal{F}_J^N \phi$) and globally ($\mathcal{G}_J^N \phi$) operators, that can also be used
 318 within the $\mathcal{P}_{\leq p}$ operator, are derived from the until operator
 319 ($\phi \mathcal{U}_J^N \phi$) as usual. We will omit the intervals J and N when
 320 they are in the form $[0, \infty)$.

321 Multiple works in the literature (e.g., [54], [55], [56])
 322 enable using additional operators to compute the proba-
 323 bility/reward of a formula or to query for the minimum and
 324 maximum probability/reward of a PRCTL formula.

325 These operators are not formally defined in PRCTL and
 326 and are usually only informally introduced in PRCTL by
 327 existing tools (e.g., [57], [58]). To enable usage of these
 328 operators in our translation, in this work, we extend the
 329 PRCTL syntax previously discussed as follows:

$$\phi \equiv \mathcal{P}_{=?}(\phi \mathcal{U}_J^N \phi) \mid \mathcal{P}_{min=?}(\phi \mathcal{U}_J^N \phi) \mid \mathcal{P}_{max=?}(\phi \mathcal{U}_J^N \phi) \mid \\ \mathcal{E}_{=?}(\phi \mathcal{U}_J^N \phi) \mid \mathcal{E}_{min=?}(\phi \mathcal{U}_J^N \phi) \mid \mathcal{E}_{max=?}(\phi \mathcal{U}_J^N \phi).$$

330 The operators $\mathcal{P}_{=?}$ and $\mathcal{E}_{=?}$ computes the probability/re-
 331 ward of the PRCTL formula $\phi \mathcal{U}_J^N \phi$ when the Markov
 332 reward model is deterministic. The operators $\mathcal{P}_{min=?}$ and
 333 $\mathcal{E}_{min=?}$ computes the minimum probability/reward of the
 334 PRCTL formula $\phi \mathcal{U}_J^N \phi$. The operators $\mathcal{P}_{max=?}$ and $\mathcal{E}_{max=?}$
 335 compute the maximum probability/reward of the PRCTL
 336 formula $\phi \mathcal{U}_J^N \phi$.

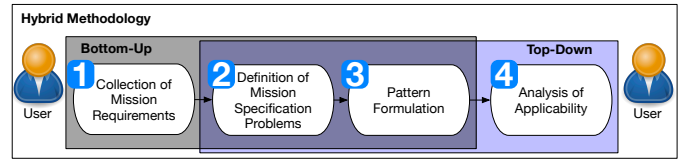


Fig. 1. Methodology used to define the mission specification patterns.

4 HYBRID METHODOLOGY TO IDENTIFY QUANTITATIVE MISSION SPECIFICATION PATTERNS

337 This section presents the *hybrid methodology* employed in this
 338 work to identify quantitative mission specification patterns. 339
 340 The hybrid methodology combines the benefits of the *bottom-*
 341 *up* and *top-down* methodologies used in the literature for
 342 defining patterns. The bottom-up methodology (e.g., [34],
 343 [35], [59], [60]) follows the intuition that patterns are solutions
 344 for recurrent problems within some specific domain. There-
 345 fore, it defines patterns by (i) performing a literature analysis
 346 to identifying recurrent mission specification problems, and
 347 (ii) formulating solutions for those problems. The top-down
 348 methodology (e.g., [61]) follows the intuition that experts
 349 can propose patterns by relying on their experience and use
 350 existing mission requirements to validate them. Therefore, it
 351 defines patterns by (i) proposing the patterns upfront, and
 352 (ii) using existing mission requirements to assess whether
 353 the proposed patterns are appropriate and useful in practice.
 354

355 The bottom-up and top-down methodologies are comple-
 356 mentary. The former exploits the data provided by the

users, i.e., mission requirements collected from the literature, for the definition of the patterns, the latter defines patterns upfront and uses the data provided by the users (i.e., mission requirements) for assessing their applicability. Both solutions have pros and cons. Since patterns are defined by considering data, i.e., the mission requirements from the literature, the bottom-up methodology is more likely to lead to patterns that are applicable in practical scenarios. However, if the set of mission requirements is limited, the catalog of patterns will only support the specification of a narrow set of missions. The top-down process is more speculative since missions are defined based on experts' experience. This may lead to a larger set of patterns. However, some of these patterns may have limited applicability. Therefore, we use a hybrid methodology that exploits the benefits of both bottom-up and top-down methodologies (Figure 1). This hybrid methodology combines the bottom-up (gray shadowed area) and the top-down (purple shadowed area) methodologies as follows:

- 1 *Collection of Mission Requirements.* This activity uses the literature to collect the mission requirements that will be used to extract the patterns (according to the bottom-up methodology).
- 2 *Definition of Mission Specification Problems.* This activity uses the mission requirements to extract the recurrent mission specification problems (according to the bottom-up methodology). It also allows the upfront addition of mission specification problems that are likely to be relevant (according to the top-down methodology).
- 3 *Pattern Formulation.* This activity requires the formulation of solutions, in terms of patterns, for the mission specification problems (according to both the top-down and the bottom-up methodologies).
- 4 *Analysis of Applicability.* This activity requires the evaluation of the applicability of the patterns in practice (according to the top-down methodology).

Steps 1, 2, and 3 (collection of mission requirement, definition of mission specification problems, and pattern formulation) are described in the following. Step 4, the analysis of applicability, is part of our evaluation (see Section 8).

All data and artifacts produced in these steps can be found in our publicly available replication package [50].

4.1 Collection of Mission Requirements

Our mission requirements were collected as follows:

- We considered all papers published in the software engineering, robotics, and formal methods venues presented in Table 2 from 2014 to 2019. The list of venues includes a subset of the top software engineering, robotics, and formal methods venues. We subsequently adopted papers published in the software engineering, robotics, and formal methods venues in 2020 and 2021 for validation purposes (see Section 8.1).
- Each venue/year combination was assigned to one of the three authors tasked with the collection of mission requirements, so that each of these authors handled a similar number of venue/year combinations.
- The authors selected papers satisfying the following criteria:

TABLE 2
List of venues considered for collecting mission requirements.

Venues	Acronym
Transactions on Robotics	TRO
International Journal of Robotics Research	IJRR
Transactions on Automation Science and Engineering	TASE
International Conference on Advanced Robotics	ICAR
International Conference on Robotics and Automation	ICRA
Transactions on Mechatronics	TMECH
Symposium on Assembly and Manufacturing	ISAM
Simulation, Modeling and Programming for Autonomous Robots	SIMPAR
Transactions on Human-Machine Systems	HMS
Formal Aspects of Computing	FAC
International Conference on Software Engineering	ICSE
Symposium on Software Reliability Engineering	ISSRE
Transactions on Software Engineering	TSE
Software Engineering and Formal Methods	SEFM
Software Engineering for Adaptive and Self-Managing Systems	SEAMS
Automated Software Engineering	ASE
Foundations of Software Engineering	ESEC/FSE
International Conference on Model Driven Engineering Languages and Systems	MODELS

- The paper title contains a movement-related concern related to the robotic domain. For example, the papers “Reconfigurable Motion Planning and Control in Obstacle Cluttered Environments under Timed Temporal Tasks” [62] and “Dynamic Routing of Energy-aware Vehicles with Temporal Logic Constraints” [63] were selected since their titles contain movement-related concerns, respectively “reconfigurable motion planning” and “dynamic routing” of “Vehicles”.
- The paper contains at least one formulation of a mission requirement involving a movement notion and additionally including a portion of the requirement related to one or more quantitative concerns (e.g., probability or time).
- Finally, the authors extracted from the paper all natural language requirements involving movement notions and quantitative concerns.

4.2 Identification of Mission Specification Problems

We identified mission specification problems starting from the mission requirements as follows:

- We divided the collected mission requirements among three of the authors.
- Each mission requirement was labeled with two types of keywords:
 - Keywords that describe the mission specification problems the robot has to achieve. Whenever a mission refers to one of the baseline mission specification patterns for robotic mission that are extended in this work, we use the name of the pattern as a keyword.
 - Keywords describing the quantitative behavior associated with the pattern.
- We created a graph structure representing semantic relations between keywords. Each keyword is associated with a node of the graph structure. Two nodes were connected if their keywords identify two similar mission specification problems.

- Nodes that were connected through edges and contained keywords that identify the same mission specification problem were merged.
- We allowed each author to propose additional mission specification problems according to the *top-down* methodology.

We finally organized the mission specification problems into a catalog represented through a graph structure that facilitates browsing the mission specification problems.

4.3 Pattern Formulation

To formulate our mission specification patterns, we analyzed each mission specification problem. For each, we formulated a mission specification pattern following established practices [34], [60], [61]. Specifically, we define a pattern by:

- a *name* that uniquely identifies the pattern;
- an *intent* that captures the purpose of the pattern, i.e., a description of the mission requirement related to the corresponding mission specification problem;
- a *template instance* that contains the mission specification associated with the pattern;
- *variations* describing possible minor changes that can be applied to the pattern;
- *examples and known uses* describing examples collected from the literature;
- *relationships* describing connections between different patterns, and
- *occurrences* describing usages of the pattern in the research literature.

We defined the mission specification of the template instance by consulting the specifications presented in the papers we surveyed and by cross-checking them.

In the next section, we describe our quantitative mission specification patterns catalog.

5 QUANTITATIVE MISSION SPECIFICATION PATTERNS CATALOG

This section presents QUARTET, our catalog of quantitative mission specification patterns. First, we detail the recurrent quantitative mission specification problems addressed by our patterns (Section 5.1). Then, we describe our proposed quantitative mission specification patterns to solve these problems (Section 5.2).

5.1 Quantitative Mission Specification Problems

For each venue that contained at least one paper satisfying our selection criteria, Table 3 contains the number of mission requirements collected for each year between 2014 to 2019 following the methodology described in Section 4. The remaining seven venues from Table 2 contained no relevant papers. The mission requirements corresponding to the years of 2020 and 2021 are set aside to be later used for validation (see Section 8.1). An example of mission requirement collected is: “*In an emergency scenario, robots shall guide the evacuees to the exit so that minimum time is spent to escape out of the indoor environment*”. This mission requirement was considered by Tang et al. [64] in a Transactions on Human-Machine Systems (HMS) paper from 2016. In total, we

TABLE 3

Number of mission requirements collected for each venue and year. NA in a cell indicates that an edition was not held/published on that year

Venue	Collected Mission Requirement							Validation		
	Year							Year		
	2014	2015	2016	2017	2018	2019	Tot.	2020	2021	Tot.
TRO	2	4	0	0	0	7	13	8	2	10
IJRR	1	0	0	0	0	3	4	0	0	0
TASE	0	1	0	0	1	2	4	0	4	4
ICRA	0	6	4	2	5	5	22	4	3	7
TMECH	0	1	0	0	0	0	1	0	0	0
SIMPAR	NA	NA	0	NA	3	NA	3	NA	NA	0
HMS	3	0	1	0	0	0	4	0	0	0
FAC	0	0	1	0	0	0	0	0	0	1
Total	6	12	6	2	9	17	51	12	9	21

* The remaining seven venues from Table 2 contained no relevant paper.

collected 51 natural-language mission requirements which involve *quantitative measures* on concerns related to robotic applications, such as energy consumption, the probability of succeeding or failing in accomplishing missions, and the time required for completing the missions. While these quantitative measures are significantly different from a mission requirement perspective, they share similarities from a specification perspective. For this reason, in the following, we do not treat such measures separately, but instead provide a set of patterns that can be applied to any of those quantitative measures.

The mission specification problems addressed by our mission specification patterns are summarized in the pattern catalogs illustrated in Figures 2a and 2b. They present *elementary* and *composite* mission specification problems, respectively. Elementary mission specification problems capture fundamental quantitative measures directly sourced and identified from the mission specification phase. Composite mission specification problems express higher-order robotics concerns. Observe their compositional nature – composite problems are a form of syntactic sugar over elementary patterns, yielding higher-order constructs. Specifically, composite mission specification problems consider cases in which the quantitative measure represents specific robotic concerns, such as time and resources. While for these cases the elementary mission specification patterns still apply (e.g., the mission designer can use the pattern that will be proposed for the ‘minimize’ problem when the quantitative measure represents time), additional problems referring to specific needs were identified (e.g., the need to pause the robot for a given time). The leaves of the tree represent *mission specification problems*. The mission specification problems identified by following the bottom-up procedure are graphically indicated with a solid border, while the mission specification problems added by the authors according to the top-down procedure are graphically indicated with a dashed border. We added mission specification problems that are strictly related to other problems covered by the patterns in the catalog. For example, we have added the mission specification problem “Less than” that is the dual of the

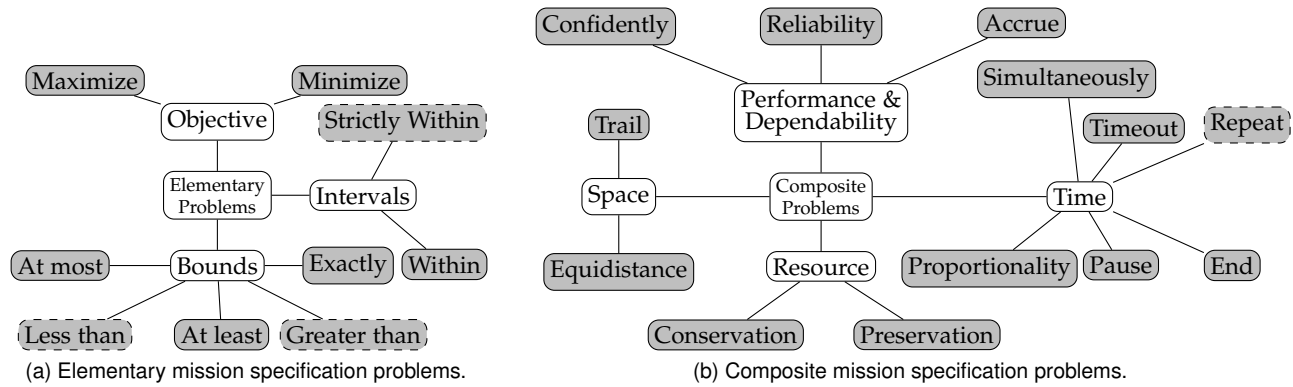


Fig. 2. Elementary and composite mission specification problems. Filled nodes: problems, non-filled nodes: categories. Nodes with solid and dashed borders respectively represent the mission specification problems identified by following the bottom-up and top-down procedures depicted in Fig. 1.

547 mission specification problem “At least”. The intermediate
 548 nodes facilitate browsing within the hierarchy and aid
 549 pattern selection and decision making. We summarize our
 550 mission specification problems in the following. Table 4
 551 provides a sample mission requirement for each mission
 552 specification problem identified by following the bottom-
 553 up procedure and provides the reference of the paper from
 554 which the requirement has been extracted.

5.1.1 Elementary Mission Specification Problems

556 The elementary mission specification problems are depicted
 557 in Figure 2a and described in the following. The elemen-
 558 tary mission specification problems are grouped into three
 559 categories: *Objective*, *Bounds*, and *Intervals*. The *Objective*
 560 category contains problems concerning the achievement of a
 561 goal. The *Bounds* category contains problems requiring the
 562 value of the quantitative measure to remain below or above
 563 certain thresholds. The *Intervals* category contains problems
 564 requiring the quantitative measure to be within certain
 565 intervals. The top part of Table 5 (column “Description”)
 566 contains a description of the respective elementary problem.

5.1.2 Composite Mission Specification Problems

568 The composite mission specification problems are depicted
 569 in Figure 2b and described in the following. Composite
 570 patterns are grouped into four categories: *Time*, *Performance*
 571 *& Dependability*, *Space*, and *Resource*. The *Time* category
 572 contains problems where the quantitative measure reflects
 573 time-related requirements. The *Performance & Dependability*
 574 category contains problems where the quantitative measure
 575 refers to probabilistic, reliability or performance aspects of
 576 the missions. The *Space* category contains problems where
 577 the quantitative measure represents spatial concerns within
 578 missions. The *Resource* category contains problems where
 579 the quantitative measure represents some resource involved.
 580 The bottom part of Table 5 (column “Description”) contains
 581 a description of each composite problem.

582 The solution to each of these recurrent mission spec-
 583 ification problems is provided by a quantitative mission
 584 specification pattern. Our quantitative mission specification
 585 patterns are detailed in the following section.

5.2 Quantitative Mission Specification Patterns

587 This section presents the QUARTET catalog. Each mis-
 588 sion specification pattern addresses a mission specification

589 problem; for example, the pattern addressing the *Maximize*
 590 problem is reported in Figure 3. The pattern contains a
 591 description of the intent (“the robotic application shall
 592 maximize the value of the quantitative measure m while
 593 performing a mission”), template specifications, variations
 594 of the pattern, examples and known uses, relationships with
 595 other patterns, and occurrences of the pattern in the literature.
 596 Examples and known uses provide exemplar usage scenarios
 597 and describe the applications of the patterns in the broad
 598 sense. Differently, occurrences provide references to works
 599 from the research literature using the patterns. Typically,
 600 occurrences contain references to works that led to pattern
 601 identification. Notice that for each pattern, alternative
 602 specifications can be provided depending on whether the
 603 quantitative measure represents time, probability, reward,
 604 or other quantitative measures. In Figure 3, two template
 605 specifications in Probabilistic Computation Tree Logic with
 606 Rewards (PRCTL) [52] are reported. The first concerns the
 607 case in which the quantitative measure represents the proba-
 608 bility of achieving a certain mission: the PRCTL specification
 609 scopes the PRCTL formula σ encoding the robotic mission
 610 with the PRCTL operator $\mathcal{P}_{max=?}$ requiring the probability to
 611 be maximized while ensuring the satisfaction of the formula
 612 σ . The second concerns the case in which the quantitative
 613 measure represents the reward collected while performing a
 614 certain mission: the PRCTL specification scopes the PRCTL
 615 formula σ encoding the robotic mission with the PRCTL
 616 operator $\mathcal{E}_{max=?}$ requiring the reward to be maximized while
 617 ensuring the satisfaction of the PRCTL formula σ .

618 A logic that provides constructs capable of expressing the
 619 mission specification of all the QUARTET patterns does not
 620 exist: neither a target logic supporting “generic” quantitative
 621 measures nor a comprehensive logic supporting (explicit)
 622 time, space, probability, and rewards is available in the
 623 literature. Therefore, we opted for selecting an interpretation
 624 for the quantitative measures and one of the logic languages
 625 proposed in the literature supporting that interpretation.
 626 Notice that the proposed patterns can be extended in
 627 the future when more expressive logics become available
 628 and that additional mission specifications targeting other
 629 languages can be proposed depending on users’ needs.

630 In this work, we considered probability and rewards as
 631 quantitative measures interpretations. For this reason, we
 632 selected PRCTL [52] (see Section 3.2) as the target logic

TABLE 4
Examples of quantitative mission requirements collected using the bottom-up methodology.

Problem	Mission requirement
Maximize	Given a team of robots [...] find a control strategy for the robotic team that yields the maximum probability of satisfying the task [39]
Minimize	Picks up an object at an initial position and moves it to a final position, minimizing the time [65]
At most	[...] the planner should find a path [...] that does not violate a maximum level of allowed risk [66]
At least	A rover on a science exploration [...] is exploring an area looking for an object of interest for scientific studies. [...] the goal would be to plan a path such that it gets connected with a minimum expected traveled distance [67]*
Exactly	Each demand needs to be serviced exactly T time units after its generation, by a vehicle present at the demand location [68]
Within	We assume a set of robots [...] we have a set of tasks each with a location, an earliest start time, a latest finish time, and a duration for each task. [...] Robots need to arrive to a task after its earliest start time and before its latest start time [...] [69]
Pause	Robots move at 10 m/s and encounter a traffic signal at every 300 m whose waiting time is [...] [70]
Timeout-deadline	Each robot is given the same time budget to collect samples and return home [71]
End	Each demand needs to be serviced exactly T time units after its generation, by a vehicle present at the demand location [68]
Proportionality	The expected duration of a navigation action is proportional to the distance between two locations [72]
Simultaneously	A robot [...] simultaneously get coffee from either machine then buy cookies and then give to person A; simultaneously to check mails and then inform person B [73]
Accrue	The robot's objective is to maximize its target classification performance at all the sites [...] [74]
Reliably	The robot is connected if it is able to reliably transfer information to the remote station [75]
Confidently	In 95% of mission executions, the robot achieves its mission [76]
Equidistance	Robots shall be uniformly distributed in an area [...] [70]
Trail	If the robot car enters lane 1, it will observe the environment car and follow it to lane 1 [77]
Conservation	A tour that visits a set of observation locations with minimum length such that each point of interest is observed by at least one complementary pair [71]
Preservation	The robot's objective is to maximize its target classification performance at all the sites, under limited onboard energy constraints (including both communication and motion), with a limited access to a human operator [...] [74]

* Our interpretation of this requirement is that "the rover shall travel at least a minimum distance".

633 since it provides support for the specification of temporal
634 properties that contain probability and rewards. We used
635 PRCTL for expressing the mission specifications of all
636 the patterns of the QUARTET catalog except the patterns
637 belonging to the *Space* category and the *Proportionality*
638 pattern since we were unable to specify these patterns in PRCTL. For
639 the patterns of the *Space* category, we use a logic proposed
640 by Wolter and Zakharyashev [78] that enables reasoning
641 about numerical distances. For the *Proportionality* pattern
642 we used the Hybrid Logic of Signals (HLS) [79], a logic-
643 based language that enables the specification of complex
644 CPS time-related requirements. Specifically, the equidistance
645 pattern was defined in the logic proposed by Wolter and
646 Zakharyashev by exploiting the binary distance operator
647 δ and by forcing the distance between the robot rob and
648 rob_1 and the robot rob and rob_2 to be equal to the value v .
649 We forced this formula to hold during the execution of the
650 mission $miss$. The trail pattern was defined by a formula
651 forcing the distance between the robot rob and the object o
652 to be equal to the value v and by requiring the formula
653 to hold during the execution of the mission $miss$. The
654 proportionality pattern was defined in HLS by using (a) two
655 signal variables m_1 and m_2 indicating that the missions $miss_1$
656 and $miss_2$ are accomplished, (b) two existential operators
657 that check for the presence of two timestamps t_1 and t_2
658 at which missions $miss_1$ and $miss_2$ are accomplished, and
659 (c) a constraint requiring the proportionality relation between
660 t_1 and t_2 by a factor v . All the patterns of the QUARTET
661 catalog are available online [50].

Name: Maximize
Intent: The robotic application shall maximize the value of the quantitative measure m while performing a mission $miss$.
Template: The following formulae encode the mission in PRCTL while performing the mission.
PRCTL: $\mathcal{P}_{max=?} \sigma / \mathcal{E}_{max=?} \sigma$
Variations: This pattern can be extended by considering other quantitative measures, such as energy saving and utility.
Examples and Known Uses: A common usage example of the Maximize pattern is to maximize time, probability, reward, and performance
Relationships: The Maximize pattern can be used in combination with the Interval and Bound patterns to set upper and lower bounds for the maximization.
Occurrences: Kloetzer and Mahulea [39] proposed a mission specification requiring a team of robots to find a strategy that yields the maximum probability of satisfying the task.

* σ refers to the PRCTL formula encoding the robotic mission.

Fig. 3. Example of Quantitative Mission Specification Pattern: Maximize.

6 PATTERN-BASED DSL

This section presents QUARTET, a DSL that enables using and combining the previously introduced 22 robotic mission specification patterns [35] and the QUARTET catalog. We present the syntax of our DSL (Section 6.1) and its semantics (Section 6.2).

6.1 Syntax of the DSL

Figure 4 presents the grammar of the proposed DSL. Optional items are enclosed in round brackets labeled with a question mark; the symbol $|$ separates alternatives.

TABLE 5
Quantitative mission specification problems and constructs of the DSL addressing the problem.

Problem	Description	DSL
Maximize	Maximize m while performing the mission $miss$.	maximize m $miss$
Minimize	Minimize m while performing the mission $miss$.	minimize m $miss$
At most	Keep m lower than or equal to v while performing $miss$.	m at most v $miss$
Less than	Keep m strictly lower than v while performing $miss$.	m less than v $miss$
At least	Keep m greater than or equal to v while performing $miss$.	m at least v $miss$
Greater than	Keep m strictly greater than v while performing $miss$.	m greater than v $miss$
Exactly	Keep m exactly v while performing $miss$.	m exactly v $miss$
Within	Keep m within the (closed) interval $[v_1, v_2]$ while performing $miss$.	m within v_1 and v_2 $miss$
Strictly Within	Keep m within the (open) interval (v_1, v_2) while performing $miss$.	m strictly within v_1 and v_2 $miss$
Conservation	Minimize the value of m performing $miss$.	conserve m while $miss$
Preservation	Keep the value of m within interval $[b_l, b_u]$ while performing $miss$.	preserve m within $[v_1, v_2]$ while $miss$
Pause	Pause the mission $miss$ for v time instants. Then, resume it.	pause v $miss$
Timeout-deadline	Execute $miss$. Stop the the execution when the timeout v is reached.	timeout v $miss$
Repeat	Repeat the mission $miss$ every v time units.	repeat $miss$ every v
End	Terminate mission $miss$ exactly at time v .	end $miss$ exactly at v
Proportionality	Keep the time to perform $miss_1$ and $miss_2$ proportional by a factor v .	time of $miss_1$ proportional to [...]
Simultaneously	Execute the actions $act_1, act_2, \dots, act_n$ simultaneously.	execute rob actions $act_1, act_2, \dots, act_n$
Accrue	Maximize the performance m while performing $miss$.	rob accrue m while $miss$
Reliably	Ensure that the measure m is higher/lower than the value v .	achieve $miss$ with reliability m [...]
Confidently	Achieve $miss$ and ensure that confidence m is higher/lower than v .	achieve $miss$ with confidence m [...]
Equidistance	rob performs $miss$ by keeping rob_1 and rob_2 at the same distance.	rob $miss$ equidistance rob_1 rob_2
Trail	rob follows object o keeping a distance v .	rob trail o with distance v

* $miss, miss_1, miss_2$ are missions; v, v_1, v_2 are values; rob is a robot, o is an object, m is the name of the quantitative measure. [...] represents portions of the DSL of Figure 4 omitted for graphical reasons.

672 The terminals of the language are $loc, rob, condition,$
673 $act, m,$ and v . The terminal loc represents a location: either a
674 logical location, e.g., a room of the building, or a physical loca-
675 tion, e.g., position x, y, z . The terminal rob indicates a robot.
676 The terminal $condition$ represents Boolean condition that
677 is true or false. The terminals $act, act_1, act_2, \dots, act_n$
678 indicate actions. The terminal m represents a quantitative
679 measure. The terminals v, v_1, v_2 are values.

680 A robotic mission can be specified as a the conjunction of
681 two missions ($miss$ **and** $miss$), disjunction of two missions
682 ($miss$ **or** $miss$), negation of a mission (**not** $miss$), a non-
683 quantitative pattern describing the task to be executed by a
684 robot (rob **shall** pat), an elementary quantitative pattern
685 (e_qpat), or a composite quantitative pattern (c_qpat).

686 The usage of the non-quantitative robotic mission spec-
687 ification patterns that QUARTET builds on (introduced
688 in Section 3.1) is enabled by the term pat . Each alternative
689 in the rule of the term pat enables the use of one of the
690 elementary patterns. The construct associated with each of
691 the 22 non-quantitative robotic mission specification patterns
692 from Table 1 is reported in the DSL column in the table. .

693 Usage of the elementary and composite patterns of the
694 QUARTET catalog is enabled by the terms e_qpat and
695 c_qpat . Each alternative in the rule of the term e_qpat
696 enables using one of the elementary patterns. Each alterna-
697 tive in the rule of the term c_qpat enables using one of the
698 composite patterns. The construct associated to each mission
699 specification problem is reported in Table 5 (column DSL).

700 **Example 2.** Referring to our running example, let us con-
701 sider for space reasons the following portion of mission
702 requirement ($m1$): “after closure, the robot $r1$ shall visit the

703 *different parts of the shop to record the items that are present*
704 *on the shelves after closure. The robots have to minimize the*
705 *time required to perform this mission”. This portion can be*
706 *expressed using the DSL in Figure 4 as follows:*

```

707         m1: minimize Time (
708 (r1 shall react instantly to close by visit CP, TA, HA)
709         and
710 (r1 shall counteract instantly when reach CP by record)
711         and
712 (r1 shall counteract instantly when reach TA by record)
713         and
714 (r1 shall counteract instantly when reach HA by record))

```

715 where $m1$: defines the robotic mission, $close$ is an event
716 indicating that the shop closure time is reached, $record$
717 is an action that records the content of the shelves in a
718 given area of the shop. We made the complete formal-
719 ization of the requirement of the Example 1 available
720 online [50].

721 A robotic mission (\mathcal{R}), expressed using the DLS specified
722 in Figure 4, is automatically translated into a mission
723 specification using a *translation function* (τ) that compiles
724 a robotic mission (\mathcal{R}) into a mission specification (\mathcal{S}) and
725 defines its semantics.

6.2 Semantics of the DSL

726 This section defines the semantics of our DSL by proposing a
727 translation that maps the constructs of the DSL that refer to
728 patterns from the QUARTET catalog into PRCTL formulae.
729 The interested reader can find the semantics of the constructs
730 of the DSL that refer to the 22 non-quantitative robotic
731 mission specification patterns from Table 1 in [35]. We do not
732 report the semantics of the DSL constructs corresponding
733

Mission	miss ::= miss and miss miss or miss not miss rob shall pat e_qpat c_qpat
Pattern	pat ::= visit (in sequence in order in strict order fairly)? locs patrol (in sequence in order in strict order fairly)? locs visit (more than less than exactly) n times loc avoid (loc until cond loc loc after cond) react (instantly with a delay promptly) to cond by (exec act pat reach loc) counteract (instantly with a delay) when reach loc by cond wait in location loc until cond
Elementary Patterns	e_qpat ::= maximize m miss minimize m miss m at most v miss m less than v miss m at least v miss m greater than v miss m exactly v miss m within v ₁ and v ₂ miss m strictly within v ₁ and v ₂ miss
Composite Patterns	c_qpat ::= conserve m while miss preserve m within [v ₁ ,v ₂] while miss pause v miss timeout v miss repeat miss every v end miss exactly at v time of miss ₁ proportional to miss ₂ by factor v execute rob actions act ₁ ,act ₂ ,...act _n rob accrue m while miss achieve miss with reliability m (greater less) than v achieve miss with confidence m (greater less) than v rob miss equidistance rob ₁ rob ₂ rob trail o with distance v
Condition	cond ::= condition is true act is ended rob in loc
Locations	locs ::= {loc (, loc)*}

* miss, miss₁, miss₂ are missions; v, v₁, v₂ are values; rob is a robot, o is an object, m is the name of the quantitative measure.

Fig. 4. The syntax of the DSL for the quantitative specification patterns for robotic missions.

Mission	$\tau(\text{miss1 and miss2}) = \tau(\text{miss1}) \wedge \tau(\text{miss2})$ $\tau(\text{not miss}) = \neg\tau(\text{miss})$	$\tau(\text{miss1 or miss2}) = \tau(\text{miss1}) \vee \tau(\text{miss2})$ rob shall pat = $\tau(\text{pat}[r \leftarrow \text{rob}])$	
Elementary Patterns	Prob.	$\tau(\text{maximize m miss}) = \mathcal{P}_{\text{max}=?}(\tau(\text{miss}))$ $\tau(\text{m at most v miss}) = \mathcal{P}_{\leq v}(\tau(\text{miss}))$ $\tau(\text{m at least v miss}) = \mathcal{P}_{\geq v}(\tau(\text{miss}))$ $\tau(\text{m exactly v miss}) = \mathcal{P}_{\geq v}(\tau(\text{miss})) \wedge \mathcal{P}_{\leq v}(\tau(\text{miss}))$ $\tau(\text{m within v}_1 \text{ and v}_2 \text{ miss}) = \mathcal{P}_{\geq v_1}(\tau(\text{miss})) \wedge \mathcal{P}_{\leq v_2}(\tau(\text{miss}))$ $\tau(\text{m strictly within v}_1 \text{ and v}_2 \text{ miss}) = \mathcal{P}_{>v_1}(\tau(\text{miss})) \wedge \mathcal{P}_{<v_2}(\tau(\text{miss}))$	$\tau(\text{minimize m miss}) = \mathcal{P}_{\text{min}=?}(\tau(\text{miss}))$ $\tau(\text{m less than v miss}) = \mathcal{P}_{<v}(\tau(\text{miss}))$ $\tau(\text{m greater than v miss}) = \mathcal{P}_{>v}(\tau(\text{miss}))$
		Rewards	$\tau(\text{maximize m miss}) = \mathcal{E}_{\text{max}=?}(\tau(\text{miss}))$ $\tau(\text{m at most v miss}) = \mathcal{E}_{[0,v]}(\tau(\text{miss}))$ $\tau(\text{m at least v miss}) = \mathcal{E}_{[v,\infty]}(\tau(\text{miss}))$ $\tau(\text{m exactly v miss}) = \mathcal{E}_{>v}(\tau(\text{miss})) \wedge \mathcal{E}_{<v}(\tau(\text{miss}))$ $\tau(\text{m within v}_1 \text{ and v}_2 \text{ miss}) = \mathcal{E}_{[v_1,\infty]}(\tau(\text{miss})) \wedge \mathcal{E}_{[0,v_2]}(\tau(\text{miss}))$ $\tau(\text{m strictly within v}_1 \text{ and v}_2 \text{ miss}) = \mathcal{E}_{(v_1,\infty)}(\tau(\text{miss})) \wedge \mathcal{E}_{[0,v_2]}(\tau(\text{miss}))$
Composite Patterns	$\tau(\text{conserve m while miss}) = \mathcal{E}_{\text{min}=?}(\tau(\text{miss}))$ $\tau(\text{preserve m within [v}_1, v_2] \text{ while miss}) = \mathcal{E}_{[v_1, v_2]}(\tau(\text{miss}))$ $\tau(\text{pause v miss}) = \mathcal{G}^{[0,v]} \tau(\neg\text{miss}) \wedge (\mathcal{F}^{[v+1, v+1]}(\tau(\text{miss})))$ $\tau(\text{timeout v miss}) = \mathcal{G}^{[v, \infty]}(\neg\tau(\text{miss}))$ $\tau(\text{repeat miss every v}) = \tau(\text{miss}) \wedge \mathcal{G}^{[0, \infty]}(\tau(\text{miss}) \rightarrow (\mathcal{G}^{[1, v-1]}(\neg\tau(\text{miss})) \wedge (\mathcal{F}^{[v, v]}(\tau(\text{miss}))))))$ $\tau(\text{end miss exactly at v}) = \mathcal{G}^{[0, v]}(\tau(\text{miss})) \wedge \mathcal{G}^{[v, \infty]}(\neg\tau(\text{miss}))$ $\tau(\text{time of miss}_1 \text{ proportional to miss}_2 \text{ by factor v}) = \text{NA}$ (Not Available in PRCTL)		
	$\tau(\text{execute rob actions act}_1, \text{act}_2, \dots, \text{act}_n) = \mathcal{F} \left(\bigwedge_{i=1}^n \text{act}_i \right)$ $\tau(\text{r accrue m while miss}) = \mathcal{E}_{\text{max}=?}(\tau(\text{miss}))$ $\tau(\text{achieve miss with reliability m (greater less) than v}) = \mathcal{E}_{[v, \infty]}(\tau(\text{miss})) / \mathcal{E}_{[0, v]}(\tau(\text{miss}))$ $\tau(\text{achieve miss with confidence m (greater less) than v}) = \mathcal{L}_{>v}(\tau(\text{miss})) / \mathcal{L}_{<v}(\tau(\text{miss}))$ $\tau(\text{rob miss equidistance rob}_1 \text{ rob}_2) = \text{NA}$ (Not Available in PRCTL) $\tau(\text{rob trail o with distance v}) = \text{NA}$ (Not Available in PRCTL)		

Fig. 5. Semantics of the DSL.

734 to the patterns belonging to the *Space* category and the
735 *Proportionality* pattern since we were unable to specify these
736 patterns in PRCTL (see Section 5.2).

737 Figure 5 presents the translation τ defining our semantics.
738 The table is divided into three parts containing respectively
739 the semantics of the mission, elementary patterns, and
740 composite patterns constructs. The translation τ defines the
741 conversion of each operator from our language into PRCTL.
742 For example, the PRCTL formula obtained by applying
743 the mapping function τ to the formula **miss and miss** is
744 the formula $\tau(\text{miss}) \wedge \tau(\text{miss})$, i.e., the conjunction of the
745 PRCTL formulae obtained by applying the translation τ to the
746 left and the right operands of the **and** operator.

747 For *mission constructs*, the definition of the translation τ
748 specifies how to convert the Boolean operators that define
749 the mission into the corresponding PRCTL operators. For the
750 construct **rob shall pat**, the PRCTL formula generated by
751 the translation ($\tau(\text{pat}[r \leftarrow \text{rob}])$) is obtained by applying
752 the translation to the term **pat** and by associating the value
753 of the term **rob** to the variable r , that will be later defined,
754 during the translation.

755 For *elementary patterns*, the definition of the translation
756 τ defined in Figure 5 behaves differently depending on
757 whether the quantitative measure refers to probability or
758 rewards. For probability, the translation of the minimum
759 and maximum constructs relies on the PRCTL operators

760 $\mathcal{P}_{min=?}$ and $\mathcal{P}_{max=?}$, respectively. For the other operators,
 761 the translation of the DSL constructs uses the PRCTL operator
 762 $\mathcal{P}_{\triangleleft p}$ by setting the value for the operator \triangleleft to $\{<, >, \leq, \geq\}$
 763 depending on the operator to be translated. For rewards, for
 764 the minimum and maximum constructs, the translation relies
 765 on the PRCTL operators $\mathcal{E}_{min=?}$ and $\mathcal{E}_{max=?}$. For rewards,
 766 the translation of the DSL constructs uses the PRCTL operator
 767 $\mathcal{E}_J(\phi)$ by setting the interval J to $[0, v]$, $[0, v)$, $[v, \infty)$ or
 768 (v, ∞) depending on the operator to be translated.

769 For *composite patterns*, we consider reward and prob-
 770 abilities as metrics to define the patterns that belong to
 771 the resource and performance and dependability categories.
 772 The translation for the *Conservation* pattern relies on the
 773 operator $\mathcal{E}_{min=?}$ that calculates the minimum reward. The
 774 translation for the *Preservation* pattern relies on the operator
 775 \mathcal{E}_J and keeps the reward within the interval $[v_1, v_2]$. The
 776 translation for the *Pause* pattern specifies that the mission is
 777 not executed (i.e., $(\neg \text{miss})$ holds) within the interval $[0, v]$
 778 (i.e., $\mathcal{G}^{[0, v]} \tau(\neg \text{miss})$ holds) and its execution re-starts at time
 779 instant $[v + 1, v + 1]$ (i.e., $\mathcal{F}^{[v+1, v+1]}(\tau(\text{miss}))$ holds). The
 780 translation for the *Timeout* pattern specifies that the mission
 781 is not executed (i.e., $(\neg \text{miss})$ holds) within the interval
 782 $[v, \infty]$ (i.e., $\mathcal{G}^{[v, \infty]}(\neg \tau(\text{miss}))$ holds). The translation for
 783 the *Repeat* pattern specifies that the formula $\tau(\text{miss})$ holds
 784 initially, and globally if the mission miss holds (i.e., $\tau(\text{miss})$
 785 holds), it will not hold for the next $v - 1$ time instants
 786 (i.e., $\mathcal{G}^{[1, v-1]}(\neg \tau(\text{miss}))$ holds), and it will hold again at
 787 time instant v (i.e., $\mathcal{F}^{[v, v]}(\tau(\text{miss}))$ holds). The translation
 788 for the *End* pattern specifies that the mission miss is in
 789 execution until the time instant v (i.e., $\mathcal{G}^{[0, v]}(\tau(\text{miss}))$ holds),
 790 and its execution stops at time v (i.e., $\mathcal{G}^{[v, \infty]}(\neg \tau(\text{miss}))$
 791 holds). We do not provide a translation for the *Proportionality*
 792 pattern since there is no construct in PRCTL that enables
 793 the specification of proportionality between time instants.
 794 The translation for the *Simultaneously* pattern specifies that
 795 eventually all the actions are performed at the same time
 796 instant. Notice that the translation proposed for the patterns
 797 belonging to the “Time” category do not follow the PRCTL
 798 syntax (i.e., the temporal formula is not preceded by the $\mathcal{P}_{\triangleleft p}$
 799 operator). Therefore, to ensure that our translation generates
 800 formulae within the PRCTL syntax, we constrain the pat-
 801 terns belonging to the “Time” category to be used within
 802 elementary patterns translated using the rules proposed for
 803 the probability metric previously presented. The translation
 804 for the *Accrue* pattern relies on the operator $\mathcal{E}_{max=?}$ that
 805 enables to maximize reward measure while performing the
 806 mission miss . The translation for the *Reliability* pattern
 807 relies on the operator \mathcal{E}_J where the interval J is set to
 808 (v, ∞) or $[0, v)$ depending on whether the **greater** or **less**
 809 **than** construct is used. The translation for the *Confidently*
 810 pattern relies on the operator $\mathcal{L}_{\triangleleft p}$ where \triangleleft is set to “>”
 811 or “<” depending on whether the **greater** or **less than**
 812 construct is used. We do not provide a translation in PRCTL
 813 for the patterns that belong to the space category since
 814 PRCTL does not explicitly support the specification of space
 815 properties.

816 7 IMPLEMENTATION

817 This section presents our proof-of-concept QUARTET tool,
 818 which supports the usage of the quantitative robotic mission

specification patterns introduced in this paper. The tool is 819
 publicly available online [50] as an Eclipse plugin. 820

821 QUARTET provides a graphical user interface (GUI) that
 822 allows engineers to define mission requirements using a
 823 the DSL presented in Figure 4. The GUI is developed using
 824 Xtext [80], a software framework for developing DSLs. A
 825 screenshot of QUARTET containing the mission requirement
 826 m1 from Example 2 is reported in the top part of Figure 6,
 827 alongside two more missions, m2 and m3. These quantitative
 828 and qualitative formulae, respectively, are derived from
 829 mission requirement m1, and are later translated into the
 830 property specification language of the probabilistic model
 831 checker PRISM.

832 QUARTET automatically translates mission requirements
 833 into PRCTL properties according to the translation reported
 834 in Figure 5. The translation is implemented in Xtend [81], a
 835 general-purpose programming language based on Java and
 836 commonly used with Xtext [80]. We selected the property
 837 specification language of PRISM [82] as a mission specifi-
 838 cation language. Our choice was made for three different
 839 reasons. First, the only publicly available tool supporting the
 840 entire PRCTL logic we found is the Markov Reward Model
 841 Checker (MRMC) [83] publicly available online [84]. How-
 842 ever, we decided to not consider MRMC since, differently
 843 than PRISM, MRMC is not currently maintained nor largely
 844 used by the academic/industrial community: the last update
 845 was made in 2011 [85]. Second, the property specification lan-
 846 guage of PRISM provides increased expressiveness compared
 847 to other existing logics: it subsumes several probabilistic
 848 logics, including PCTL [51], CSL [86], probabilistic LTL [87],
 849 and PCTL* [88]. Therefore, while not being able to express
 850 all the formulae of the PRCTL logic, our conjecture is that
 851 many of our requirements could be expressed using the
 852 property specification language of PRISM. The validity of
 853 our conjecture is assessed by our evaluation (see Section 8.2).
 854 Third, the property specification language of PRISM is used
 855 by many other tools, such as EvoChecker [89], [90], a search-
 856 based approach that employs evolutionary algorithms to
 857 automate model synthesis. Therefore, the mission specifica-
 858 tions generated by QUARTET can be fed into various model
 859 checking and synthesis tools.

860 To ensure that our tool generates mission specifications
 861 expressed in the property specification language of PRISM,
 862 we constrained the DSL in Figure 4 to (a) prohibit nested
 863 probabilities, (b) accept only LTL properties for the reward
 864 and probability operators, and (c) prohibit the definition of
 865 specifications that lead to the conjunction of quantitative and
 866 non-quantitative PRISM formulae since such formulae can
 867 not be processed by PRISM. The first constraint forbids the
 868 creation of formulae that nest probabilities operators, such as
 869 the formula $\mathcal{P}_{max=?}(\mathcal{P}_{min=?} \sigma)$ that is nesting the operator
 870 $\mathcal{P}_{min=?}$ within $\mathcal{P}_{max=?}$. The second constraint forces the
 871 formulae used within the reward and probability operators
 872 to be LTL formulae, such as $\phi_1 \mathcal{U} \phi_2$, i.e., it does not enable
 873 the exploitation of the values assumed by J and N within
 874 formulae of the form $\phi_1 \mathcal{U}_J^N \phi_2$. Finally, the third constraint
 875 forbids the definition of formulae of type $\phi_1 \wedge \phi_2$ where
 876 one of ϕ_1 and ϕ_2 uses probabilistic operators and the other
 877 does not. For example, the formula $\phi_1 \mathcal{U} \phi_2 \wedge \mathcal{P}_{max=?} \phi_3 \mathcal{U} \phi_4$,
 878 which can be generated by our translation, is not supported
 879 by PRISM. If these constraints are not satisfied, QUARTET

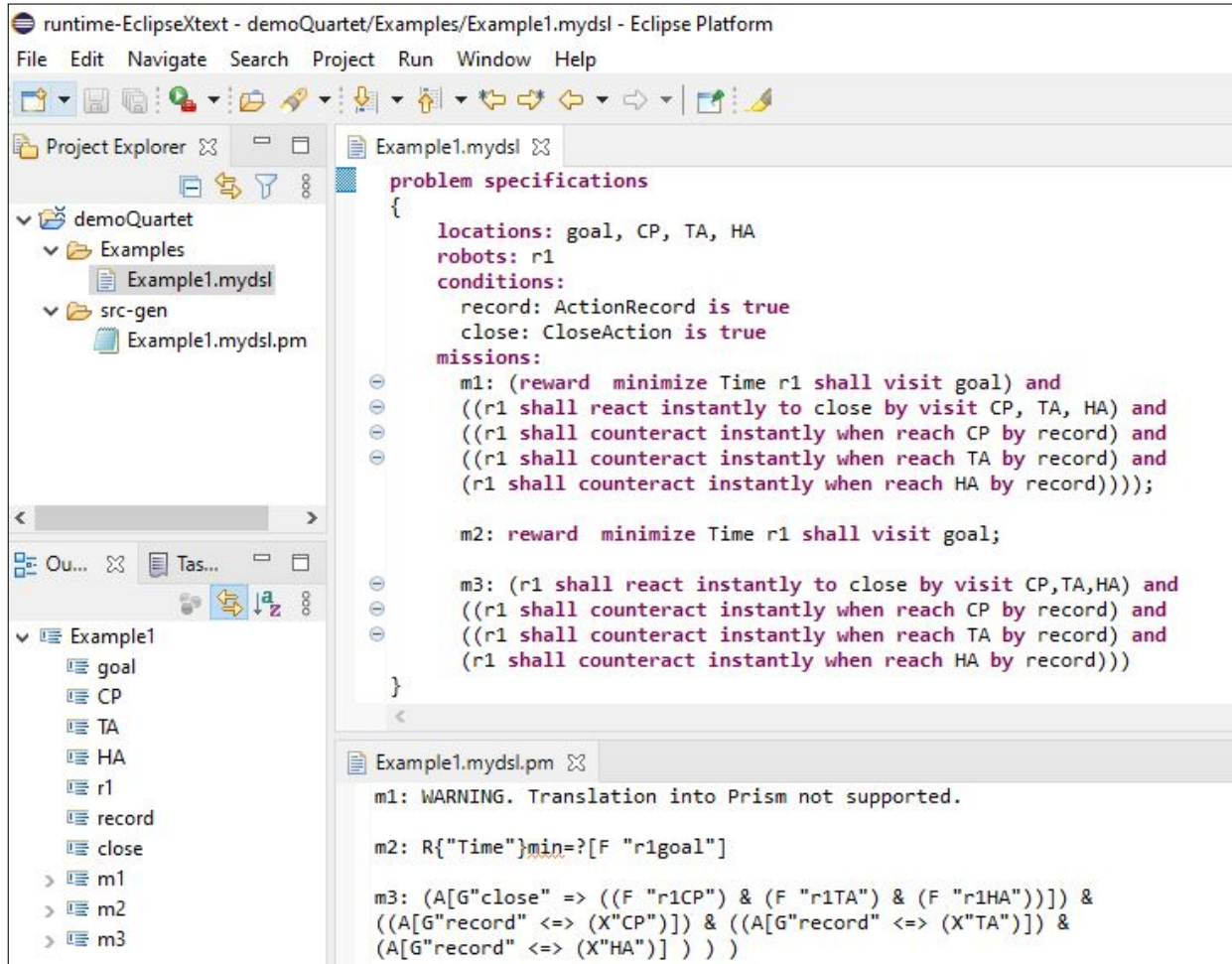


Fig. 6. Screenshot of QUARTET containing the portion of the mission requirement of Example 2 (mission m1). The problem specifications shows the necessary locations (goal, CP, TA and HA), robots (r1) and conditions (record and close). Missions m2 and m3 are derived from m1 as quantitative and qualitative formulae, respectively, translated automatically into Prism (bottom part). Mission m1 cannot be translated directly into Prism as it joins (by a logical “and”) a number (from m2) and a Boolean (from m3).

880 generates a warning indicating that the mission specification
 881 in the property specification language of PRISM cannot
 882 be generated. If the constraints are satisfied, QUARTET
 883 outputs the mission specification in the property specification
 884 language of PRISM. The mission specification generated
 885 by QUARTET for the portion of the mission requirement
 886 of Example 2 (m1), and its derived missions (m2, m3) is
 887 reported in the bottom part of Figure 6. For mission m1, our
 888 tool generates a warning since constraint (c) is violated: the
 889 translation leads to a conjunction of a quantitative and a
 890 non-quantitative PRISM formula. Such formulae can not be
 891 processed by PRISM.

892 8 EVALUATION

893 This section assesses our quantitative robotic mission spec-
 894 ification patterns by considering the following research
 895 questions:

- 896 • *RQ1* (Coverage of the patterns). What is the coverage of
 897 the QUARTET patterns? (Section 8.1)
- 898 • *RQ2* (Applicability of the translation). In how many
 899 cases can the translation be applied? (Section 8.2)

- 900 • *RQ3* (Exploitability of the mission specification). How
 901 can the mission specification generated by the transla-
 902 tion be used in practice? (Section 8.3)

903 *RQ1* assesses the coverage of our patterns (see Section 5)
 904 according to our hybrid methodology and as mandated by
 905 the top-down methodology (see Section 4). Our patterns
 906 are designed to cover recurrent robotic mission specification
 907 problems. Therefore, they are not exhaustive. Given a set of
 908 mission requirements, *RQ1* verifies whether our patterns can
 909 express these requirements.

910 *RQ2* assesses the applicability of our translation method
 911 in practice (see Section 5.2). Since our translation considered
 912 probability and rewards as quantitative measures interpre-
 913 tations and PRCTL as target logic, it does not support
 914 some of the DSL constructs (see constructs labeled ‘NA’
 915 in the Table 5). In addition, due to the limitations of the
 916 property specification language of PRISM, we added a set
 917 of constraints (see Section 7) to ensure that our mission
 918 specification is within the PRISM input language. *RQ2*
 919 assesses how these factors limit the applicability of our
 920 translation in practical cases.

921 *RQ3* assesses the usefulness of our mission specification
 922 in practical scenarios. The mission specification generated

TABLE 6

Number of times each of our patterns was used to express a (part of) a mission requirement of our dataset.

Pattern	#N	Pattern	#N	Pattern	#N
<i>Maximize</i>	5	<i>Strictly Within</i>	1	<i>Reliability</i>	4
<i>Minimize</i>	6	<i>Conservation</i>	5	<i>Proportionality</i>	-
<i>At most</i>	3	<i>Preservation</i>	4	<i>Simultaneously</i>	1
<i>Less than</i>	-	<i>Pause</i>	-	<i>Accrue</i>	3
<i>At least</i>	3	<i>Repeat</i>	1	<i>Confidently</i>	-
<i>Greater than</i>	-	<i>End</i>	-	<i>Equidistance</i>	-
<i>Exactly</i>	2	<i>Timeout</i>	5	<i>Trail</i>	-
<i>Within</i>	2				

TABLE 7

Evaluation of applicability of patterns identified via the top-down procedure.

Pattern	Example
<i>Less than</i>	[...] while keeping the distance between them lower than 3.6 meters. ([92]-Section 4.1)
<i>Greater than</i>	[...] β is changed from less than $\pi/2$ to greater than $\pi/2$ when the robot passes by an obstacle. ([93]-Section 3.2.5) The muscle activation is constrained to the range between 0 and 1. ([94]-Section 2.4) [...] repeat this message every 30 seconds ([95]-pg. 24).

923 by our translation (e.g., the PRCTL formula) supports
924 automated reasoning (e.g., as an input for model checking
925 and synthesis tools).

926 All the material, data, and results of our evaluation are
927 publicly available [50].

928 8.1 RQ1 — Coverage of the Patterns

929 To assess the coverage of our mission specification patterns,
930 we first collected a set of mission requirements from the
931 literature, and then we assessed whether our patterns
932 enabled expressing these requirements.

933 *Dataset.* We considered a benchmark of 21 requirements
934 (see the Validation column of Table 2), collected from the
935 years of 2020 and 2021 by following the same methodology
936 presented used to define the QUARTET patterns (see Sec-
937 tion 4.1). We followed a *train-test split* approach, popular in
938 evaluation of machine learning and data science research, by
939 considering collection of six years of requirements for the
940 bottom-up pattern formulation, and subsequently evaluating
941 coverage against requirements collected the last two years.

942 *Methodology.* We considered each of the 21 mission
943 requirements of the dataset and proceeded as follows. Three
944 of the authors analyzed each of the mission requirements
945 and attempted to use the DSL in Figure 4 to express it. If it
946 was possible to formulate it using the constructs provided
947 by the DSL, the patterns were deemed sufficiently expressive
948 to capture the mission requirement. If it was not possible
949 to completely express the mission requirement using the
950 constructs provided by our DSL, we identified the portion of
951 the requirement that could not be expressed.

952 *Results.* The QUARTET patterns were able to completely
953 express 20 out of the 21 requirements (~95%), and to partially
954 express 1 requirement (~5%). This coverage is acceptable for
955 practical applications since the patterns are (by definition)
956 not intended to be exhaustive. Therefore, these mission re-
957 quirements were formalised using our DSL. The requirement
958 we could not be express prescribed the robot to “adapt the
959 velocity profile of the robot, according to the wireless channel
960 measurements” [91]. This requirement relates the values of
961 two measures: “velocity” and “wireless channel measure”.
962 However, each pattern captures a mission specification
963 problem related to *one* quantitative measure. Extending our
964 pattern catalog to support mission specification problems
965 that relate two quantitative measures is one of our future
966 work directions (see Section 10).

967 Recall that to express one mission requirement, the DSL
968 allows more than one pattern to be used. The number of

969 times each of our patterns was used to express a (part
970 of) a mission requirement from our dataset is reported in
971 Table 6. The results show that to express these mission
972 requirements, we used 14 patterns out of the 22 mission
973 specification patterns in our catalog (~64%). The patterns
974 *Pause*, *End*, *Confidently*, *Equidistance*, *Trail*, *Proportionally* were
975 not used to specify any of the requirements of the benchmark
976 (demonstrating over-coverage of the patterns catalog). This
977 result is not surprising since we only collected instances
978 of mission requirements occurring in papers published in
979 the two years considered. It is worth noting that patterns
980 introduced via the bottom-up procedure have been defined
981 according to mission requirements that have been found in
982 literature, as shown in Table 4. So, the fact that we have not
983 found additional instances may imply that these patterns
984 are less popular than, for instance, *Minimize*, which has the
985 highest occurrence.

986 The patterns defined through the top-down procedure
987 (depicted with dashed borders in Figure 1) require special
988 attention, since they are based on a hypothesis and are not
989 sourced from examples collected from the literature. The
990 results in Table 6 show that the QUARTET patterns *Less*
991 *than* and *Greater than* were not used to specify any of the
992 mission requirements. Therefore, to confirm the usefulness of
993 these patterns, we performed a dedicated search for mission
994 requirements that require these patterns for being specified.
995 The purpose of our ad-hoc search was to confirm patterns’
996 usefulness – we were searching for mission requirements that
997 required specified patterns. To this end, we used snowballing
998 techniques and queried search engines, such as Google
999 Scholar, with search strings that were pattern specific. Our
1000 procedure is sound: if we found a mission requirement that
1001 required the pattern, then the pattern was useful to specify at
1002 least one mission requirement. Table 7 provides a portion of
1003 an example mission requirement from the literature for each
1004 of these patterns. The complete natural language description
1005 of the mission requirements is available online [50].

The answer to RQ1 is that our quantitative patterns were able to fully express 20 out of the 21 mission requirements of the benchmark (~95%), while 1 (~5%), partially. To do so, 14 (~64%) out of 22 patterns of the catalog were employed. Additionally, for each pattern identified and defined through a top-down procedure, we were able to locate examples in the literature, indicating its usefulness and appropriateness.

8.2 RQ2 — Applicability of the Translation

To evaluate the applicability of our translation, we considered the requirements defined for RQ1 and verified the number of cases on which our translation (Table 5) could be applied. Our goal is to evaluate how the applicability of our translation in practical cases is influenced by the lack of support for some of the DSL constructs (NA labeled entries in Table 5) and the constraints added to ensure that our mission specification is within the PRISM specification language (see Section 7).

Dataset. We considered the benchmark of 20 mission requirements from RQ1 that were expressible in our DSL. This dataset contains 14 patterns out of the 22 mission specification patterns of our catalog (see Table 6).

Methodology. We considered each of the 20 mission requirements of our dataset. We applied our translation by running the automated support provided by QUARTET. We recorded whether the translation was applicable or not. When the translation was applicable, we stored the mission specification generated by QUARTET.

Results. Our translation was applicable for 15 out of the 20 mission requirements expressible using our DSL (75%). For the 5 remaining cases, the lack of support for some of the DSL constructs (which are labeled ‘NA’ in Table 5) prevents the application of the translation. Among the 15 cases for which our translation was applicable, in seven cases our translation lead to a warning, since the constraints added to ensure that our mission specification is within the PRISM specification language (Section 7) were not respected. In these cases, the PRISM tool does not support the PRCTL formulae generated by our translation. In the other cases, our translation produced a mission specification that could be processed by PRISM.

Our results show that our translation provides reasonably large applicability: it was applicable to 75% of our requirements. When our translation was applicable, in more than 50% of the cases, the mission requirements could also be processed by PRISM. Notice that our applicability will increase over time as (a) more expressive logics are defined by the research community, and (b) efficient tools that support more complex logic formulae are proposed.

The answer to RQ2 is that our translation was applicable for 15 out of the 20 mission requirements expressible using our DSL (75%). When our translation was applicable, PRISM could process the mission specifications generated by our translation in a reasonably large number of cases (more than 50%).

8.3 RQ3 — Exploitability of the Mission Specification

This question aims to assess the exploitability of the (PRISM) mission specifications generated by QUARTET, i.e., to assess how researchers and engineers can use these specifications. To assess the exploitability of mission specifications (e.g., for synthesis or model checking) one would need to assume some type of underlying model, e.g., discrete-time Markov reward models, used as input for synthesis or model checking. However, manually devising models would introduce significant threats to the validity of our results. For this reason, we opted for collecting mission requirements from the literature that were accompanied with a PRISM

specification already proposed by the respective authors. Then, we analyzed the mission requirements considered by the authors, and we checked if the mission requirements could be expressed using our DSL. If the mission requirement was expressible using our DSL, we used our DSL to model the mission requirement. We verified whether QUARTET generated the PRISM mission specification defined by the authors. If this was the case, we considered the results reported in the publication and discuss how the specification was exploited by the authors for automated reasoning (e.g., model checking or synthesis).

Dataset. Our dataset consists of 16 requirements. Out of these 16 requirements, 2 are robotic requirements collected from the PRISM Case Studies webpage [96], and 14 were collected by the authors using search engines. Specifically, we searched for publications containing both the mission requirements and the corresponding PRISM specifications that were exploiting them (for any purpose). Requirements from RQ1 could not be reused, since PRISM specifications were not included in the corresponding publications.

Methodology. We considered each of the 16 mission requirements of our dataset. First, we checked if we were able to express the requirement using our DSL. If this was the case, we modeled the mission requirement using our DSL. We used QUARTET to automatically generate the mission specification. We checked whether the mission specification matched the one considered by the authors of the paper. Specifically, we checked whether the specifications entail the same functional behavior by manually analyzing and comparing the semantics of the specifications. If this was the case, we extracted from the publication the objective for which the mission specification was used (e.g., synthesis or model checking) and we analyzed the results obtained by the authors using the automated support provided by PRISM. We discussed how the specification was exploited for automated reasoning.

Results. All the requirements of our case studies were expressible using our DSL. The mission requirements, the DSL formulations and the mission specifications are publicly available [50]. The mission specifications obtained using QUARTET matched the ones reported by the authors within their papers. In 25% of the cases (4 out of 16) the specifications were used for model checking tools, in 75% of the cases (12 out of 16) the specifications were used for synthesis. The mean model checking and synthesis times reported in the publications using these specifications are 222s and 1688s, respectively. This shows that the mission specifications produced by QUARTET could be exploited effectively.

The answer to RQ3 is that the specifications generated from 16 mission requirements can be used for synthesis and model checking. Based on the publications surveyed, these activities can also be performed in reasonable time: the average of the maximum times required to perform model checking and synthesis were respectively 222s and 1688s.

8.4 Discussion and Threats to Validity

The proposed quantitative patterns were able to express ~95% of the 21 requirements of the benchmark dataset (Section 8.1). This is an extensive coverage for practical

1116 applications since patterns are (by definition) not meant
 1117 to be exhaustive: they target *recurrent* mission specification
 1118 problems. Additionally, new specification problems and
 1119 patterns may be defined and the catalog can be extended
 1120 over time. Observe that elementary constructs express funda-
 1121 mental concerns within quantitative specification, as well as
 1122 their encoding in typical languages. Composite patterns are
 1123 intended to bring specifications closer to the robotics domain
 1124 at hand. The number of mission requirements analyzed is in
 1125 line with other approaches in the field [34], [37], [59], [60];
 1126 however, we acknowledge the possible presence of bias in
 1127 requirements collection since humans were involved in the
 1128 (non-automated) process. We counter this by making our
 1129 dataset available to serve as a reproduction kit [50].

1130 Formal mission specification is a difficult and error-prone
 1131 process [27], and facilities that enable mission designers
 1132 to employ high-level reasoning – instead of low-level but
 1133 precise specifications – are highly desired. A recent study [97]
 1134 provided empirical evidence that pattern-based languages,
 1135 such as the DSL proposed in this work, are easier to
 1136 understand than logic-based languages. Such is the rationale
 1137 of the composite patterns: a designer can utilize composite
 1138 patterns for specification, while enjoying the benefits of their
 1139 precise and unambiguous formal specification *under the hood*.
 1140 Translation of composite pattern DSL formulations to low-
 1141 level specifications in formal languages allows the use of
 1142 planners and automated engineering techniques such
 1143 as code generation or software synthesis, while avoiding
 1144 ambiguities that might exist in informal representations, since
 1145 the semantics of composite patterns are precisely defined. If
 1146 some application demands it, coverage can be extended by
 1147 specifying additional application-specific patterns over the
 1148 elementary ones.

1149 Our translation was applicable for the 75% of the mission
 1150 requirements expressible using the DSL (see Section 8.2). For
 1151 the five cases in which the translation was not applicable,
 1152 the hindrance was the limited expressiveness of PRCTL
 1153 that did not enable us to propose a translation for some
 1154 of the constructs of our DSL (entries labeled ‘NA’ in Table 5).
 1155 When our translation was applicable, PRISM could process
 1156 the mission specifications in more than 50% of the cases.
 1157 This problem is caused by the current limitations of PRISM,
 1158 which does not support the full PRCTL logic, thus forcing
 1159 us to introduce syntactic constraints for definition of the
 1160 mission requirements. We believe such problems will be
 1161 addressed over time: our translation will be extended as
 1162 more expressive logics – and tools with more expressive
 1163 input languages – become available. Finally, we note that in
 1164 the present work we provided translations only in PRCTL.
 1165 Other translations that target other logics may be developed
 1166 as well. We showed that the mission specifications generated
 1167 from 16 mission requirements can be used for synthesis
 1168 and model checking (see Section 8.3) and that based on the
 1169 publications surveyed, these activities can be performed in
 1170 reasonable, practical time. We acknowledge that additional
 1171 uses of the mission specifications generated by QUARTET
 1172 are possible, and that the list we presented in Section 8.3 is
 1173 not exhaustive.

1174 Our patterns do not currently support multi-robots,
 1175 robotic arm tasks, and swarm of robots. However, they can be
 1176 used as building blocks for DSLs tailored to the specification

of these types of missions.

1177 An empirical investigation should be performed to assess
 1178 in an end-to-end manner whether the approach helps in
 1179 practice robotics engineers – as target users of QUARTET–
 1180 in specifying and reasoning about their quantitative mission
 1181 requirements, and whether the concepts it implements are
 1182 captured in language constructs. Such an assessment should
 1183 include not only the coverage of the DSL but also auxiliary
 1184 aspects such as usability, providing valuable future extension
 1185 directions.

1186 QUARTET is integrated with PRISM, an existing model
 1187 checker and synthesis tool. PRISM can process the mission
 1188 specifications produced by QUARTET. It can use the mission
 1189 specifications for model checking, i.e., the mission speci-
 1190 fications produced by QUARTET are properties that can
 1191 be verified on a system model. PRISM can also use the
 1192 mission specifications for synthesis via PRISM-games [98].
 1193 PRISM-games extends PRISM by supporting the synthesis of
 1194 stochastic multi-player games representing competitive and
 1195 collaborative behaviors. Specifically, PRISM-games synthe-
 1196 sizes optimal player strategies which ensure that a property
 1197 holds. The mission specifications produced by QUARTET can
 1198 be considered as properties that the synthesized component
 1199 has to ensure. Finally, our translation (Section 6.2) can be
 1200 extended to support the languages of other synthesis tools,
 1201 such as Uppaal Stratego [99].

1202 In certain mission-critical domains, robots may not be
 1203 able to accomplish the full-fledged mission. A typical sce-
 1204 nario specifies one or multiple degraded versions of the
 1205 mission. In some scenarios, the robot may need to change
 1206 its configuration to continue a mission or a behavior. These
 1207 reactive behaviors can be specified by using the “Trigger
 1208 patterns” specified in Table 1. These patterns, which express
 1209 a robot reactive behaviour based on stimuli, or a robot’s
 1210 inaction until a stimulus occurs, are presented in our previous
 1211 work [35].

1212 *Threats to Validity.* The selection of the venues from which
 1213 the mission requirements were collected is subject to a
 1214 selection bias that may impact the external validity of our
 1215 results as it influences their generalizability to applications
 1216 not covered in these venues. The selection of the mission
 1217 requirements used for answering our research questions
 1218 is also a threat to external validity since it influences the
 1219 extent to which our results can be generalized. Specifically,
 1220 in this work, we considered mission requirements involving
 1221 movement-related concerns (see Section 4.1) since specifying
 1222 robotic movement is a critical aspect for robotic mission spec-
 1223 ification. To mitigate this threat, we collected requirements by
 1224 considering both robotic mission requirements co-designed
 1225 with robotic application stakeholders (including researchers,
 1226 developers, operators, and end-users) and papers (from
 1227 diverse authors) from different venues (software engineering,
 1228 robotics, and formal methods). Empirical studies will con-
 1229 sider over time larger and more diverse sets of requirements
 1230 as done with property specification patterns for temporal
 1231 properties [97].

9 RELATED WORK

1232 This section presents related work that supports engineers
 1233 in expressing system requirements and generating specifica-
 1234
 1235

tions by either defining patterns or by proposing Domain Specific Languages (DSL) for the robotic domain.

Pattern Definition. Specification patterns to support engineers in writing logic-based formulae are present in the research literature. Dwyer et al. [34] defined specification patterns for LTL formulae. Konrad and Cheng [59] defined patterns that consider real-time properties. Grunske et al. [60] defined patterns that considered probabilistic properties. Autili et al. [61] combined and extended the previous catalogs patterns. While these patterns target generic logic-based formulae they are not tailored for the robotic domain.

Specification patterns were applied in a large variety of domains, such as security [100] and safety [101], service-based applications [102], decentralized systems [103], cyber-physical systems [104], [105], and Machine Learning (ML) [106]. Specification patterns were also largely applied in the robotic domain. For example, patterns were proposed for supporting the development of code for robotic software components [107], predicting human activities in human-robot collaborative assembly tasks [108], exploring and prototyping human-robot interactions (e.g., [109], [110], [111]). However, these patterns do not target generic robotic missions. In an earlier work [36], [37], three of the authors of this paper proposed a set of robotic mission specification patterns. However, these patterns do not enable the specification of the quantitative aspects of the robotic mission.

DSLs for the robotic domain. There is a large variety of DSLs for the robotic domain. The interested reader can refer to existing surveys from the literature (e.g., [15], [112], [113], [114], [115], [116]). Most of the existing DSLs are procedural (or imperative using the terminology in [15]), and therefore require their users to model explicitly the control flow of the robot [15]. Instead, a declarative specification of the mission is more convenient since the control flow is implicit and the users just need to model the goal of the mission. This is the case of specification languages that have been built on top of some temporal logic. In these languages, the specification of the goal of the mission is then given as input, e.g. to a logic-based planner, which then computes automatically the control flow of the robot. The drawback of logic-based languages is their usability and limited user-friendliness. Specification patterns contribute to solving this problem. They typically offer a structured English grammar enabling the natural-language-like formulation of mission requirements. The need for supporting engineers in writing natural-language-like mission requirements and automatically generating mission specifications is also highlighted in the recent survey by Dragule et al. [15]. An interesting DSL that combines the procedural and declarative style is Promise [21], [45]. This language builds on top of our previous mission specification patterns [35], [36], [37]. The patterns are the main building blocks of the language, and the DSL introduces operators (fallback, alternatives, sequence, parallel, etc.) that enable the composition of patterns to build complex missions involving one or more robots. The DSL we propose in this paper builds on top of the DSL proposed in [35], [36], [37]. We anticipate that our catalog of patterns can be exploited to build DSLs that can further contribute to advancing the area of robotic mission specification. Examples of such DSLs include DSLs enabling the specification of mission for multirobots, DSLs conceived to enable verification, as will be discussed later,

and DSLs focusing on specific application domains, such as agriculture or healthcare. Indeed, existing DSLs are specific to the service robotic domain, but there can be another step of specialization of the languages, towards application domains, as envisioned in [117]. Our patterns represent an important step towards the construction of this envisioned ecosystem of DSLs, by providing the main building blocks, with clear and well-defined semantics, on which to build. Moreover, the patterns are built on collected examples from literature, and therefore their expressiveness is anchored into the actual needs of users from this domain, as documented in their papers. Also, unlike existing DSLs, which are usually obtained starting from a target specification language (e.g., some logic language supported by a model checker), our patterns are language agnostic. New translations targeting other specification languages can be added in the future.

Finally, most of the DSLs proposed by the literature do not support the specification of quantitative aspects such as probability and rewards.

Patterns Usage. Patterns within robotics have been employed for communication, production and analysis of behavior descriptions, verification and synthesis. Efforts to provide support for mission specification have also focused on graphical tools that simplify the specification of temporal logic formulae [12], [13], [14], for which integration of pattern-based tools for robotics have also been proposed [36]. Finally, synthesis – generation of a correct-by-construction reactive system from a temporal logic specification [118], is highly relevant to robotics applications, for which patterns can be readily used – patterns previously devised by the authors have GR(1) options. GR(1) is a fragment of LTL with an efficient polynomial time synthesis algorithm. Cho et al. [119] relies on signal temporal logic to develop a control strategy synthesis method for dynamical robotic systems.

10 CONCLUSION

This paper presents QUARTET, a novel catalog of 22 specification patterns for the specification of quantitative robotic missions developed using a hybrid methodology that combines the benefits of bottom-up and top-down approaches. It further defines a pattern-based DSL to support the usage of both existing mission specification patterns and the QUARTET quantitative mission specification patterns. We proposed a translation that maps the constructs of the DSL into Probabilistic Reward Computation Tree Logic (PRCTL) formulae, precisely defining the semantics of the language and enabling the usage of existing model checking and synthesis tools. We developed a tool that supports the usage of our pattern-based DSL, enabling engineers to express complex behaviors involving quantitative concepts and directly interface with PRISM. We evaluated the coverage of the patterns of the QUARTET catalog, the applicability of our translation, and the exploitability of the logic formulae generated by our translation. Our results show that the coverage of our quantitative patterns supports the practical usage of our catalog, our translation is largely applicable, and that the mission specifications generated by our translation can be used for synthesis and model checking in practical applications. Finally, we make all of our artifacts publicly available to enable study replication [50].

In future work, we will extend our pattern catalog to further increase its coverage by supporting additional specification problems, such as relating two different quantitative measures (see Section 8.1). In addition, a promising avenue of future work entails proposing alternative specifications for the QUARTET patterns by considering other logics that can address the limitations of our translation (see NA fields of Table 5 and Section 8.2), such as ones with spatio-temporal features [120]. Finally, as has been done for specification patterns for temporal properties [97], empirical studies can assess the applicability of the mission specification patterns over additional case studies and benchmarks (see Section 8.3).

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