Safety Controller Synthesis for Collaborative Robots

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Abstract—In human-robot collaboration (HRC), software-based automatic safety controllers (ASCs) are used in various forms (e.g., shutdown mechanisms, emergency brakes, interlocks) to improve operational safety. Complex robotic tasks and increasingly close human-robot interaction pose new challenges to ASC developers and certification authorities. Key among these challenges is the need to assure the correctness of ASCs under reasonably weak assumptions. To address this need, we introduce and evaluate a tool-supported ASC synthesis method for HRC in manufacturing. Our ASC synthesis is: (i) informed by the manufacturing process, risk analysis, and regulations; (ii) formally verified against correctness criteria; and (iii) selected from a design space of feasible controllers according to a set of optimality criteria. The synthesised ASC can detect the occurrence of hazards, move the process into a safe state, and, in certain circumstances, return the process to an operational state from which it can resume its original task.

Index Terms—Controller synthesis, human-robot collaboration, software engineering, probabilistic model checking.

I. INTRODUCTION

An effective collaboration between industrial robot systems (IRSs) and humans [1], [2] can leverage their complementary skills, but is difficult to achieve because of uncontrolled hazards and unexploited sensing, tracking, and safety measures [3]. Such hazards have been studied since the 1970s, resulting in elaborate risk taxonomies based on workplaces, tasks, and human body regions [2], [4]–[10]. The majority are impact hazards (e.g., unexpected movement, reach beyond area, dangerous workpieces, hazardous manipulation), trapping hazards (e.g., operator in cage), and failing equipment. Addressing these hazards involves the examination of each mode of operation (e.g., normal, maintenance) for its hazardous behaviour, and the use of automatic safety controllers (ASCs) to trigger mode-specific safety measures [2]. Malfunction diagnostics (e.g., fault detection, wear-out monitoring) can further inform the ASC. As shown in Tab. I, a variety of safety measures [3] can prevent or mitigate hazards and accidents by reducing the probability of their occurrence and the severity of their consequences. There are functional measures using electronic equipment (e.g. speed & separation monitoring) and intrinsic measures not using such equipment (e.g, fence, flexible surface). Functional measures focusing on the correctness and reliability of a controller are called dependability measures [5], [11]. Functional measures are said to be passive if they focus on severity reduction (e.g., force-feedback control), active otherwise (e.g., safety-rated monitored stop).

The standardisation of safety requirements for IRSs [4] culminated in ANSI/RIA R15.06, ISO 10218 [12], 13482, and 15066. According to ISO 10218, an IRS comprises a robot arm, a robot controller, an end-effector, and a workpiece (see, e.g., Fig. 2a below). In collaborative operation, the operator and the IRS (called a cobot [13]) can occupy the collaborative workspace (i.e., a subset of the safeguarded workspace) simultaneously while the IRS is performing tasks [14]. Based on that, ISO 15066 recommends four safety modes, described and combined with work layouts in [8], [15]:

- safety-rated monitored stop (powered but no simultaneous activity of robot and operator in shared workspace),
- hand-guided operation (zero-gravity control, guided by an operator, no actuation without operator input),
- speed & separation monitoring (speed continuously adapted to distance of robot and operator), and
- power & force limiting (reduced impact on the human body, a robot’s power and applied forces are limited).

In the following, we highlight recent challenges and explain how our work addresses these.

Challenges: Since the 1980s, tele-programming and simulation have led to a reduction of hazard exposure. However, guarding arrangements interfere with manufacturing processes and mobile robots. Complex tasks require continuous and close human-robot interaction (e.g. mutual take-over of tasks), and mobile robots. Complex tasks require continuous and close human-robot interaction (e.g. mutual take-over of tasks), mutual clarification of intent, and trading off risk [15], [16]. Robot movements need to be predictable and impacts on the human body need to be attenuated (e.g. speed & separation monitoring requires stereo vision and laser scanners to distinguish safety zones). Engineers need to consider a variety of complex failure modes. This situation implies requirements and design spaces for ASCs, so engineers want to answer questions such as:

- Which ASC design minimises the probability of incidents in presence of human and sensor errors?

| Stage | Type of Measure | Examples |
|-------|----------------|----------|
| Hazard prevention | 1. safeguard/barrier fence, interlock | verified safety controller |
| | 2. IT safety | security-verified (safety) controller |
| | 3. IT security | |
| Hazard mitigation & accident prevention | 4. reliability | fault-tolerant scene interpretation |
| | 5. workspace intru- | speed & separation monitoring, |
| | sion detection | safety-rated monitored stop |
| | 6. shift of control | hand-guided operation |
| Accident mitigation (alleviation) | 7. power & force limitation | low weight parts, flexible surfaces; |
| | | variable impedance, touch-sensitive, |
| | | & force-feedback control |
| | 8. system halt | emergency stop, dead-man’s switch |
• Which design minimises nuisance to the human, maximises productivity, etc. while maintaining safety?
• Does a selected controller correctly handle hazards when detected and return the system to a useful safe state?

**Contributions:** We introduce a tool-supported method for the synthesis of discrete-event ASCs that meet safety requirements and optimise process performance for human-robot cooperation (alternative use of shared workspace) and collaboration (simultaneous use of shared workspace, with close interaction) [8], [17]. We model the manufacturing process and its safety analysis as a Markov decision process (MDP) and select a correct-by-construction ASC from a set of MDP policies. We extend our notion of risk structures [18] and our tool YAP [19]. This simplifies the modelling of activities and actors, critical events (CEs, e.g. hazards), mitigations (e.g. safety mode changes) and reward structures for risk optimisation; and automates the translation of risk structures into MDPs. Our approach facilitates the verification of safety of the MDP and of probabilistic reach-avoid properties of a selected policy. A verified ASC detects hazards and controls their mitigation by (i) the execution of a safety function, (ii) a transition to a safer mode, or (iii) a transition to a safer activity.

**Overview:** Sec. II discusses related work, Sec. III introduces our case study as a running example, and Sec. IV provides the theoretical background. We describe and evaluate the ASC synthesis method in Sec. V and Sec. VI, respectively, and we conclude with a short summary in Sec. VII.

II. RELATED WORK

To the best of our knowledge, our method is the first end-to-end approach to synthesising ASCs for handling multiple risks in HRC for manufacturing processes.

Askarpour et al. [20] discuss a discrete-event formalisation of a work cell in the linear-time temporal language TRIO. Actions are specified as pre/inv/post-triples (with a safety invariant) for contract-based reasoning with the SAT solver Zot. In contrast, our approach builds on probabilistic guarded command language (pGCL), separating action modelling from property specification. Beyond counterexamples for model repair, our approach yields an executable policy. While their use of a priority parameter helps to abstract from unnecessary state variables, we propose guards to implement flexible individual action orderings. Moreover, violations of inv lead to pausing the cell whereas our approach can deal with multiple mitigation options offering a variety of safety responses.

For generic robot applications, Orlandini et al. [21] employ the action language PDDL for modelling and timed game automata for controller synthesis. The model checker UPPAAL-TIGA is used for verifying (i.e., finding winning strategies for) reach-avoid properties of type A(safe U goal). While game solving could enhance our verification approach, our method focuses on guidance in risk modelling for safely optimised HRC performance. Cesta et al. [22] present an approach to synthesise controllers (i.e., plans) for HRC applications using a timeline-based PDDL planner. While they distinguish controllable (i.e., duration known) from uncontrollable actions (i.e., duration unknown), an important aspect of HRC modelling, their focus is on task planning and scheduling rather than on risk modelling for verified synthesis of ASCs.

Heinzmann and Zelinsky [23] propose a power & force limiting mode always active during an HRC activity described as a discrete-event controller. Long et al. [24] propose a speed & separation monitoring scheme with nominal (max. velocity), reduced (speed limiting), and passive (hand-guided operation) safety modes. While these authors do not aim at synthesis or task modelling, their elaborate safety modes may serve as a target platform to our multi-risk synthesis approach.

III. RUNNING EXAMPLE: MANUFACTURING COBOTS

Fig. 1 shows an IRS manufacturing cell at a UK company (with the pictures anonymised for confidentiality reasons) and replicated in a testbed at the University of Sheffield (Fig. 1c). The corresponding process (call it P) consists of activities (Fig. 2b) collaboratively repeated by an operator, a stationary robotic arm, and a spot welder (Fig. 2a). Previous safety analysis (i.e., hazard identification, risk assessment, requirements derivation) resulted in two sensors (i.e., a range finder in Fig. 1a and a light barrier in Fig. 1b, indicated in red) triggering an emergency stop if a person approaches the welder or enters the workbench while the robot or welder are active. Tab. II shows our partial safety analysis of the cell following the guidance in Sec. I. The right column specifies safety goals against each accident and controller requirements (e.g. mode-switch requirements) handling each latent cause in the left column, and indicating how the hazard is to be removed.

IV. PRELIMINARIES

Our method uses MDPs as a formal model of P, and MDP policies as the design space for controller synthesis.

**Definition 1.** Markov decision process (MDP). Given all distributions Dist(αP) over an action alphabet αP of a process P, an MDP is a tuple $\mathcal{M} = (S, s_0, \alpha_P, \delta_P, L)$ with a
Table II: Our partial safety analysis of the manufacturing cell referring to the measures recommended in ISO 15066

| Id | Critical Event (Risk Factor) | Safety Requirement | Safety Goal |
|----|-------------------------------|--------------------|-------------|
| RC | Robot arm harshly Collides with operator | The robot shall avoid harsh active collisions with the operator. | The robot shall avoid active contact with the operator. |
| WS | Welding Sparks cause operator injuries | The welding process shall reduce sparks injuring the operator. | The welding process shall reduce sparks injuring the operator. |
| RT | Robot arm Touches the operator | The robot shall avoid active contact with the operator. | The robot shall avoid active contact with the operator. |

| Latent Cause (to be mitigated timely) | Controller Requirement |
|-------------------------------------|------------------------|
| HRW | The robot shall perform a safety-rated monitored stop and (r) resume normal operation after the operator has left the shared workbench. | (m) The robot shall perform a safety-rated monitored stop and (r) resume normal operation after the operator has left the shared workbench. |
| HW | If the robot moves a workpiece to the bench then it shall switch to power & force limiting mode and (r) resume normal operation after the operator has left the bench. | (m) The robot shall perform a safety-rated monitored stop and (r) resume normal operation after the operator has left the shared workbench. |
| HC | The robot shall perform a safety-rated monitored stop and (r) resume normal idle mode with a reset procedure after the operator has left. | (m) The robot shall perform a safety-rated monitored stop and (r) resume normal idle mode with a reset procedure after the operator has left. |

Figure 2: Conceptual setting (a) and activities in the manufacturing process (b) performed by the operator, the robot, and the welder (in blue), classified by the activity groups moving and base (in gray)

set $S$ of states, an initial state $s_0 \in S$, a probabilistic transition function $\delta_P : S \times \alpha_{AP} \rightarrow \text{Dist}(\alpha_{AP})$, and a map $L : S \rightarrow 2^{\text{AP}}$ labelling $S$ with atomic propositions $\text{AP}$.

Given a map $A : S \rightarrow 2^{\text{AP}}$, $|A(s)| > 1$ signifies non-deterministic choice in $s$. Its resolution for $\delta_P$ forms a policy.

Definition 2. Memoryless Policy. A memoryless policy is a map $\pi : S \rightarrow \text{Dist}(\alpha_{AP})$ s.t. $\pi(s)(a) > 0 \Rightarrow a \in A(s)$. $\pi$ is deterministic if $\forall s \in S \exists \alpha \in A(s) : \pi(s)(\alpha) = 1 \land \forall a' \in \alpha_{AP} \setminus \{a\} : \pi(s)(a') = 0$.

The following discussion is restricted to deterministic memoryless policies. Let $\Pi_{AP}$ be the set of all such policies for $M$. Then, action rewards defined by a map $\gamma_{\text{action}} : S \times \alpha_{AP} \rightarrow \mathbb{R}_{\geq 0}$ allow the assessment of $\Pi_{AP}$ based on a quantity $q$.

Verification of $M$ is based on probabilistic computation tree logic (PCTL) whose properties over $\text{AP}$ are formed by

$$\phi ::= \top | a | \neg \phi | \phi \land \phi | \mathbf{E} \phi | \mathbf{A} \phi$$

with $a \in \text{AP}$; an optional bound $b \in \mathbb{N}_+$ for $U^{b}$ with $\sim \in \{<,=,\geq\}$; the quantification operators $P_{\sim b} = \exists \phi$ to verify (or with $=\exists$ to quantify) probabilities. $S_{\sim b} = \exists \phi$ to determine long-run probabilities. $\mathbf{R}^b = \exists \phi$ to calculate reachability and accumulative action rewards, and the abbreviations $F \phi \equiv \top \cup \phi$, $G \phi \equiv \neg F \neg \phi$, and $\phi W \psi \equiv \phi \cup \psi \lor G \phi$. For sake of brevity, consider the treatment of PCTL in [25], [26].

The concise definition of $\delta_P$, the behaviour of $\mathcal{P}$, is facilitated by PRISM’s pGCL. Guarded commands are of the form $[\alpha] \gamma \rightarrow v$ where $\alpha$ is an event label and $v$ a probabilistic update applicable to $s \in S$ only if $s \models \gamma$, where $\gamma$ is an expression in the propositional fragment of PCTL. Generally, $v ::= \pi_1 : v_1 + \cdots + \pi_n : v_n$ with $\Sigma_{i \in 1 \cdots n} \pi_i = 1$ and assignments $v_i$ to state variables of type $\text{B, N, or R}$.

For safety analysis, we view the cell in Sec. III as a process $\mathcal{P}$, monitored and influenced by an ASC to mitigate hazards and prevent accidents. An accident $a \in S$ is an undesired consequence reachable from a set $\Xi \subseteq S$ forming the causes of a. The fraction of a cause $c \in \Xi$ not related to the operator is called a hazard $h$ [27], [28]. We call $c$ latent if there are sufficient resources (e.g. time for removing $h$ by transition to $s \notin \Xi$) to prevent the accident. $h$ includes states in $S \setminus \Xi$ being critical because certain events (e.g. an operator action) cause a transition to $\Xi$, and possibly $a$, if $h$ stays active, further conditions hold, and no safety measures are put in place timely.

Risk modelling can be facilitated by specifying risk factors and combining them into risk structures [18]. A risk factor $f$ is a labelled transition system (LTS) modelling the life cycle of a critical event (i.e., hazard, cause, mishap), $f$ has the phases inactive ($f^0$), active ($f^1$), and mitigated ($f^\dagger$) and transitions between these phases signifying endangerment events ($c$) and mitigation ($m$) and resumption ($m^\dagger$) actions. Let $F$ be a set of factors, e.g. the ones in column Id in Tab. II. The Cartesian product of the phases of the factors in $F$ yields the risk space $R(F)$. To utilise factor LTSs for the translation of ASC designs into pGCL, we further develop the notion of risk factors in Sec. V-B as part of our contribution.

V. APPROACH: SAFETY CONTROLLER SYNTHESIS

Fig. 3 shows the steps and artefacts of the proposed method detailed below and illustrated with a running example.

1 We use $\rightarrow$ to separate guard and update expressions and $\rightarrow$ both for logical implication and the definition of mappings.

2 As opposed to immediate causes reducing the possibilities of risk handling.
Modelling the Manufacturing Process

Activities in $\mathcal{P}$ (Fig. 2b) are structured by sets of guarded commands. We distinguish actions of controllable actors (e.g. robot arm, welder, operator) and the ASC, and events of a sensor module and shared “manipulables” (e.g. workpiece support). $S$ is built from discrete variables (cf. Fig. 4) capturing the world state (e.g. robot location; workbench status), sensory inputs (e.g. range finder), control outputs (e.g. robot behaviour, notifications), user inputs (e.g. start button), and modes (e.g. current activity, safety mode).

Mode variables (e.g. $\text{ract}, \text{safmod}$) are used to specify a filter $\phi_a$ for enabling actions that form an activity (e.g. grab workpiece, move arm to welder), or a filter $\phi_{am}$ for enabling actions in a particular safety mode. Thus, the structure of guarded commands for $\mathcal{P}$ follows the pattern

$$[\alpha] \omega \wedge \phi_{am} \wedge \phi_a \wedge \gamma \rightarrow \nu$$

with an action label $\alpha$, a guard $\omega$ to prevent from leaving the final state, a check $\gamma$ of individual conditions, and an update expression $\nu$ (cf. Sec. IV). Given a set $S_{am}$ of safety modes, modelling involves the restriction of guarded commands of all actors in $\mathcal{P}$, by adding $\phi_{am}$ and $\phi_a$ to their guards, to obtain mode- and activity-aware guarded commands.

Example 1. Fig. 5 specifies the two robot actions $\text{r\_moveToTable}$ and $\text{r\_grabLeftWorkpiece}$ of the activity $\text{exchWrp}$.

B. Safety Analysis and Risk Modelling

Fig. 6 further develops the notion [18] of a risk factor $f$ towards guidance in the formalisation of hazards, causes, and mishaps and the events forming a causal chain (e.g. a mishap event leads to a mishap state). Based on that, $f$ supports the design of hazard mitigations to reduce accidents, and accident alleviations to reduce consequences. Hence, each critical event needs to be translated into a risk factor. Example 2 instantiates $f$ with the hazard HC from Tab. II.

Example 2. For the hazard HC, Fig. 6 describes:
(a) how an endangerment $e'$ activates HC (i.e., leads to a risk state $\rho HC \in R(F)$ where the predicate $HC$ holds true),
(b) how mitigations (e.g. issuing an operator notification) update $P$ to enter the phase $BTC$ (i.e., HC is false),
(c) further mitigations (e.g. waiting for operator response),
(d) resumptions (e.g. switching from speed & separation monitoring to normal) that update $P$ to return to phase $BTC$ where both HC and BTC are false,
(e) further endangerments (e.g. erroneous robot movement) re-activating HC from state $BTC$,
(f) a mishap event moving $P$ into a state with $HC$ true (i.e., an f-accident occurs),
(g) alleviations to handle consequences of HC in phase $BTC$.

Phase $f'$, reachable by non-deterministic or probabilistic choice, models an undetected endangerment (e.g. because of a faulty range finder for HC) that can lead to $f$. For sake of simplicity, the endanger choices in $\overline{f}$ and $\overline{f}'$ are not shown. $\overline{f}$, $\overline{f}'$, and $0f$ form the $f$-safe region of $\mathcal{P}$. Example 3 explains how one models risk for the welding activity in YAP script.

Example 3. First, the Activity section of Fig. 7 specifies that welding includes the specification of the activity moving and that the activity exchWrp is a successor of welding. This way, one specifies an activity automaton for $\mathcal{P}$ as shown in Fig. 2b.

Next, the HazardModel section lists critical events relevant to welding, the two mishaps RC and RT and the latent cause HC (cf. Tab. II). One can hypothesise high-level relationships between critical events using constraints, e.g. RC requires NOF (2HRW, HS, HC 2) expresses the assumption that exactly two of the listed events have to have occurred before RC can occur. Such relationships are typically identified during preliminary hazard operability studies (HazOp), system FMEA, or system FTA.

Furthermore, HC is specified by (a) an informal description, (b) a guard describing its activation $HC$, (c) mis (i.e., an action, e.g.
Figure 6: Phases and actions of a risk factor $f$. ⇒...multiple optional actions considered, ——minimum amount of information to be provided for a risk factor, ——optional modelling aspects.

Activity {include moving; successor exchWrkp;}
HazardModel {
  RC requiresNOf (2|HRW,HS,HC |2);
  RT requiresNOf (1|HRW,HS,HC);
  HC desc "(H)uman (C)lose to active welder and robot working"
  mitDeniesMit (HRW,HS,HC,RT);
  guard "hACT_WELDING & hloc=atWeldSpot"
  detectedBy (SHARE.HCdet)
  mitigatedBy (SHUTDOWN.HCmit,SHUTDOWN.HCmit2)
  resumedBy (NOTIFY.HCres,NOTIFY.HCres2)
  mis="h exitPlant"
  prob=0.2 // of mishap if HC not detected OR not mitigated timely
  sev=5; }

Figure 7: YAP risk model for the welding activity from Fig. 2b

Probabilistic choice in $M$ can be used to model several uncertainties. Informed by FTA and FMEA, one can consider sensor and actuator faults. In our example, the range finder as the detector of $e^HC$ fails by 5% when the operator enters the cell. Informed by HazOp, human errors can be modelled similarly. In our example, with a 10% chance, the operator enters the cell, knowing that robotArm and welder are active. Moreover, one can model the probability of occurrence of a mishap under the condition of an active hazard. In our example, with a 20% chance, $HC$ may follow $HC'$ (i.e., HC remains undetected because of the aforementioned sensor fault) or $HC$ (i.e., the ASC is not reacting timely).

C.3 Designing Mitigation and Resumption Options

The capabilities of actors in $P$ determine the controllability of critical events. We found three techniques useful in designing mitigations and resumptions: action filters (i.e., safety modes, cf. Sec. 1), activity changes (e.g. change from welding to off), and safety functions (e.g. notification). Recall that mitigations and resumptions are actions (i.e., transition labels in a risk factor LTS). Accordingly, the example in

mode HCdet desc "range finder"
guard "hACT_WELDING & rngDet=close"
embodiedBy rngDet;
mode HCmit desc "protective emergency stop of robotic system"
event stop
update "(notif'=leaveArea)"
  target (act=off, safmod=stopped)
disruption=10
nuisance=2
effort=1;
mode HCres desc "resumption from emergency stop"
event resume
guard "notif=leaveArea & !hST_HOinSGA"
update "(notif'=ok)"
target (act=exchWrkp, safmod=normal);

Figure 8: YAP action specifications for the risk factor HC

// Critical event predicates
// HCmonitor "(H)uman (C)lose to active welder and robot working"
formula RCE_HC = hACT_WELDING & hloc=atWeldSpot;
formula CE_HC = hACT_WELDING & rngDet=close;

Figure 9: Monitor predicates for HC generated for the PRISM model

Fig. 8 specifies details about the actions referred to in Fig. 7. Here, the following parameters drive the design space of an ASC: (a) a detectedBy reference (i.e., associating the guard with a sensor predicate), (b) a mitigatedBy reference to one or more mitigation options, and (c) a resumedBy reference to one or more resumption options. For this approach, we extended YAP’s input language to develop these actions into guarded commands.

Example 4. As an example for (b), in Fig. 8, the action HCmit of type SHUTDOWN (i) synchronises with the robotArm and welder on the event stop, (ii) update models a safety function, issuing a notification to the operator to leave the safeguarded area, and (iii) target switches the manufacturing cell to the activity off and to the safety mode stopped, all triggered by the range finder.

Indicated in Fig. 6, HCmit models one option for $m^{HC}$. One can distinguish several such options by quantities such as disruption of the manufacturing process, nuisance of the operator, and effort to be spent by the machines. In combination with processing time and value for each nominal action of $P$, these quantities enable the evaluation and selection of optimal policies as we shall see below.

This part of the YAP model can be translated into pGCL. Endangerments are translated into commands of the form

$[e'] \phi_{\chi} \land \zeta \rightarrow f'$ and $[e'] \phi_{\chi} \land \zeta \rightarrow (1-p) : f + p : f'$

with guards including a hazard condition $\chi$ and a corresponding monitoring (or sensor) predicate $\zeta$. Constraints, such as requiresNOf in Example 3, are then used to derive part of $\chi$.

Example 5. Fig. 9 indicates the transcription of guard and detectedBy into a pair of predicates, RCE_HC describing actual states, and CB_HC signifying states monitored by the range finder, where $p$ can denote the sensor fault probability.

Mitigations are translated into commands of the form

$[m_{t}] \phi_{f} \land f \rightarrow \nu_{f}$ and $[m_{t}'] \phi_{sm',s_{t},f'} \land f \rightarrow \bar{f}$
with $t \in \{sm, a, sf\}$ in $\phi_t$ for checking permission in the current safety mode, activity, and state of safety functions, and in $\upsilon_t$ for hazard removal by switching into a safer activity $a'$, a safer mode $sm'$, and by applying the safety function $sf'$. These updates are checked by $\phi_{sm',a',sf'}$ to be able to proceed to $\bar{f}$. Resumptions are translated into commands of the form

$$[m_{t}^{x}, \phi_{t} \land \rho_{t}] \rightarrow \upsilon_{t}$$

and

$$[m_{t}^{x}, \phi_{sm',a',sf'} \land \rho_{t}] \rightarrow 0^{f}$$

where $\phi_{t}$ guards the resumption based on the safety mode and function in place, $\rho_{t} \subseteq R(F)$ restricts permission to risk states (Sec. IV and Fig. 6) with $f$ mitigated; and $\upsilon_{t}$ inverts the safety function ($sf^{-1}$), relaxes to the safety mode $sm'$, and returns to an, ideally more productive, activity $a'$ of $P$.

D. 4 Verified Controller Synthesis

The present approach follows a two-staged search through the ASC design space: The first stage is carried through by YAP when generating the guarded commands. The second stage is performed by PRISM when synthesising MDP policies. For search space reduction, YAP employs risk gradients between safety modes and activities in the first stage. For the second stage, YAP generates reward structures for some of the quantities introduced in Sec. V-C.

1) Guarded Command Generation: The generation of $\upsilon_{t}$ for mitigations and resumptions requires the choice of a safety mode and activity to switch to, depending on the current mode and activity. Given activities $S_a$ and modes $S_{sm}$, two skew-diagonal risk gradient matrices $\Theta_{a} \in \mathbb{R}_{[S_s]} \times [S_s]$ and $\Theta_{sm} \in \mathbb{R}_{[S_{sm}] 	imes [S_{sm}]}$, e.g. manually crafted from safety analysis, can resolve this choice based on the following justification.

Assume $a_1, a_2 \in S_a$ vary in physical movement, force, and speed. If $a_1$ means more or wider movement, higher force application, or higher speed than $a_2$, then a change from $a_1$ to $a_2$ will likely reduce risk. Hence, a positive gradient is assigned to $\Theta_{a_1a_2}$. Similarly, assume $m_1, m_2 \in S_{sm}$ vary $P$'s capabilities by relaxing or restricting the range and shape of permitted actions. If $m_1$ permits stronger capabilities than $m_2$, then a change from $m_1$ to $m_2$ will likely reduce risk. Again, we assign a positive gradient to $\Theta_{sm}$. The diagonality of $\Theta$ provides the dual for resumptions where a negative gradient of the same amount from $m_2$ to $m_1$ is assigned to $\Theta_{sm}$.

Let current safety mode $c$ and mitigation $m_t$ with target mode $t$. $m_t$ changes to only if the gradient from $c$ to $t$ is $\geq 0$ ($\leq 0$). If $\Theta_{sm} \geq 0$, then a switch to $t$ is included in $\upsilon_{sm}$, otherwise $\upsilon_{sm}$ leaves $M$ in $c$. We implemented this scheme for activities analogously.

Example 6. Fig. 10 shows the result of applying this scheme in the generation of an ASC for the risk factor HC based on Fig. 8.

Essentially, $\Theta$ approximates the change of risk in case of a change from one activity or safety mode to another. Using $\Theta$, the majority of an ASC can be described in YAP script.

2) MDP Verification: This step requires establishing $\mathcal{M} \models \phi_{of} \land \phi_{t}$ with properties expressed in PCTL (Sec. IV). $\phi_{of}$ is a well-formedness property including the verification of, e.g. hazard occurrence and freedom of pre-final deadlocks, and the falsification, e.g. that final states must not be initial states. $\phi_{of}$ helps to simplify model debugging, decrease model size, guarantee progress, and reduce vacancy. $\phi_{t}$ specifies safety-carrying correctness including, e.g. ASC progress (and across cycles, liveness), particularly, that $\Pi_{\mathcal{M}}$ (i.e., the ASC design space) contains complete mitigation paths from critical events. Tab. III lists examples of $\phi_{of}$ and $\phi_{t}$ to be verified of $\mathcal{M}$.

3) Policy Synthesis: The ASC design space ($\Pi_{\mathcal{M}}$) is created by commands (e.g. mitigations, resumptions) simultaneously enabled in $s \in S$, yielding multiple policies for $s$ and some commands enabled in multiple states, giving rise to a policy for each ordering in which these commands can be chosen.

An optimal policy $\pi^{*}$, including the ASC decisions, can be selected from $\Pi_{\mathcal{M}}$ based on multiple criteria (e.g. minimum risk and nuisance, maximum productivity). For that, $\mathcal{M}$ uses action rewards to quantify (i) productivity, up- and down-time of $P$; (ii) factor-, mode-, and activity-based risk; risk reduction potential; disruptiveness and nuisance; resource consumption; and effective time of the ASC.

Example 7. Fig. 11 shows a pGCL fragment generated by YAP.

4) Discrete-time Markov chain (DTMC) Verification: Due to known restrictions in combining multi-objective queries and constraints in PRISM, part of the verification applies to the policy as a DTMC. This step requires establishing $\mathcal{M} \models \phi_{of} \land \phi_{t}$ with properties expressed in PCTL (Sec. IV). $\phi_{of}$ is a well-formedness property including the verification of, e.g. hazard occurrence and freedom of pre-final deadlocks, and the falsification, e.g. that final states must not be initial states. $\phi_{of}$ helps to simplify model debugging, decrease model size, guarantee progress, and reduce vacancy. $\phi_{t}$ specifies safety-carrying correctness including, e.g. ASC progress (and across cycles, liveness), particularly, that $\Pi_{\mathcal{M}}$ (i.e., the ASC design space) contains complete mitigation paths from critical events. Tab. III lists examples of $\phi_{of}$ and $\phi_{t}$ to be verified of $\mathcal{M}$.

Figure 10: PRISM model fragment generated for the risk factor HC.
Figure 11: PRISM rewards for risk from HC and nuisance of HCmit

Figure 12: Bird’s-eye view of the policy synthesised for the query $R_{\text{max}}^{\text{init}}[C] \land R_{\leq s}^f[C]$. Nodes are the states reachable in $\mathcal{M}$ from $s_0$, including HC-safe states (green), HC-unsafe states (orange), and mishap states (red). Edges indicate robotArm and welder actions (red), actions of the operator (black), the ASC (green), and cycle termination (blue). The gray fragment is magnified in Fig. 13.

Figure 13: Table III: Examples of checked properties and queried objectives

| Property† | Description |
|-----------|-------------|
| $v: \text{EF}(f \land \neg final)$ | Can the hazard $f$ occur during a cycle of $\mathcal{P}$? |
| $f_0: \text{EF}(\text{deadlock} \land \neg final)$ | Are all deadlock states final? Does $\mathcal{P}$ deadlock early? |
| $f_0: \text{EF} \neg f$ | Is $f_0$ inevitable? |
| $f_0: \exists s \in S: \text{final} \land \text{init}$ | Are there initial states that are also final states? |
| $v: \text{EF} \neg \text{final}$ | Can $\mathcal{P}$ finish a production cycle? |

Table III: Examples of checked properties and queried objectives

| Property† | Description |
|-----------|-------------|
| $R_{\text{max}}^\text{init}[C] \land R_{\leq s}^f[C]$ | Assuming an adversarial environment, select $\pi$ that maximally utilises the ASC. |
| $R_{\text{max}}^\text{prod}[C] \land R_{\leq s}^\text{prod}[C] \land \neg\text{rinit}[C]$ | Select ASC that maximises productivity constrained by risk level $r$ and expected severity $s$. |
| $R_{\text{max}}^\text{prod}[C] \land R_{\leq s}^\text{prod}[C]$ | Select ASC that maximises productivity constrained by exposure $p$ to severe injuries. |

Cycle-bounded correctness $\phi_\gamma$ of a policy $\pi$ (or the policy space $\Pi_{\mathcal{AM}}$)

| Property | Description |
|-----------|-------------|
| $v: \text{AF}(A \rightarrow X f)$ | Does the ASC on all paths immediately detect the hazard $A$? |
| $v: \text{AF}(f \rightarrow (\text{AF f} \rightarrow (\text{AF f})))$ | Does the ASC lively handle hazard $f$ in all situations? |
| $v: \text{EF}(f \land \text{final})$ | Does the ASC resume $\mathcal{P}$ so it can finish its cycle after $f$ has occurred? |
| $v: \text{P}_{>p}[\text{G} \neg \text{mishap}]$ | Is the probability of mishap freedom greater than $p$? |

| Property | Description |
|-----------|-------------|
| $v: \text{S}_{<p}[\text{mishap}]$ | Is the steady-state (long-run) probability of any mishap $f$ below $p$? |

VI. EVALUATION

In this section, we discuss the adequacy and efficacy of the proposed method from several viewpoints.

A. Research Questions and Evaluation Methodology

Based on the questions raised in Sec. I, we investigate the (i) scalability and performance of the approach and (ii) the effectiveness of the ASCs synthesised by it, asking:

**RQ1** How well can the approach deal with multiple hazards and mitigation and resumption options? What are the resulting model sizes and analysis times?

**RQ2** What is the likelihood of incident/accident-free operation under the control of the synthesised ASCs?

**RQ3** Which process overheads are to be expected of an ASC implementation?

For **RQ1**, we consider as inputs and parameters a YAP risk model and a PRISM MDP model of the cell (with YAP template placeholders), a single initial state of these models where all actors are in the activity $off$ and no hazard is active. Accordingly, we prepare and analyse multiple increments of

Example 8. Fig. 12 provides a bird’s eye view of a synthesised policy. States coloured in green form the set HC-safe, i.e., states in which HC is inactive or mitigated.

Fig. 13 shows a fragment of Fig. 12. Note the 5% chance of a sensor failure from state 90 leading to state 92 (i.e., the operator has approached the robotArm and welder) where HC will remain undetected and not handled. Otherwise, in state 93, HC will be mitigated after the next work step of the robotArm and welder leading to state 202. From there, the ASC mitigates to a protective stop (state 176), and resumes to state 178 (i.e., where the operator has left the safeguarded area) from where the current manufacturing cycle can be finished (state 33).
the risk model, each adding one critical event, mitigation options, and constraints to the model.

For RQ2, let $\Xi \subseteq S$ be the set of non-accident $F$-unsafe states, i.e., states labelled with at least one critical event, describing the abstract state where any critical event has at least been sensed by the ASC (e.g. $CE_{HC}$ with its handling not yet started, i.e., $0^{HC}$). For MDPs, we evaluate accident freedom with

$$P_{\sim A} \equiv \min_{f \in \{\text{min}, \text{mean}, \text{max}\}} [\neg \text{mismatch W safe}] \quad (1)$$

where $f \in \{\text{min}, \text{mean}, \text{max}\}$. For $\Xi$, Formula (1) requires the ASC to minimise the probability of mishaps until an $F$-safe state (i.e., $S \setminus \Xi$) is reached. In Tab. IV, $[\mu]$ denotes the triple comprising min, the arithmetic mean $\mu$, and max. $P_{\sim A}$ aggregates these three probabilities over $\Xi$.

Next, we synthesise policies for each of the MDP increments for the three optimisation queries

$$R_{\text{pot}}^\text{max} = [F \text{ final}] \land P_{\text{max}} = ?[C], \quad (a)$$
$$R_{\text{prod}}^\text{max} = [F \text{ final}] \land P_{\text{max}} = ?[C], \quad (b)$$
$$R_{\text{eff}}^\text{max} = ?[C], \quad (c)$$

where $\text{final}_l = \{s \in S | s \in \text{final} \land \text{all tasks finished}\}$. In the spirit of negative testing, Formula (a) aims at maximising the use of the ASC (i.e., approximating worst-case behaviour of the operator and other actors) while maximising the probability of finishing two tasks, i.e., finishing a workpiece and carrying through cell maintenance. This query does not take into account further optimisation parameters defined for mitigations and resumptions. As opposed to that, Formula (b) fosters the maximisation of productivity, any combination of decisions allowing the finalisation of tasks is preferred, hence, transitions leading to accidents or the use of the ASC are equally neglected. While Formula (c) also forces the environment to trigger the ASC, these policies represent the best ASC usage in terms of nuisance and effort. Because of constraints in the use of $R_{\text{min}}$ for MDPs, we maximise costs interpreting positive values as negative (e.g. the higher the nuisance the better).

For the experiment, we used YAP 0.5.1 and PRISM 4.5, on GNU/Linux 5.4.19 (x86, 64bit), and an Intel(R) Core i7-8665U with up to 8 CPUs of up to 4.8 MHz, and 16 GiB RAM. Tab. IV shows the data collected from seven models created for RQ1 and RQ2. The result $[\mu] = [1, 1, 1]$ for a policy denotes 100% conditional accident freedom. This desirable result is most often achieved with Formula (c) due to the fact that simultaneity of decisions of the environment and the ASC in the same state is avoided by focusing on rewards only specified for ASC actions. Such rewards model the fact that an ASC is usually much faster than an operator. Formulas (a) and (b) show poorer accident freedom because productivity rewards given to the environment compete with rewards given to the ASC to exploit its risk reduction potential.

For demonstration of YAP’s capabilities, the incident RT and the accident RC are included in the risk model without handler commands. However, these factors add further constraints on $R(F)$ to be dealt with by the ASC. Hence, $mr$ stays at 15 actions and $c$ rises to 15 constraints. In model 7 (last line of Tab. IV), the $\Xi$-fraction of $S$ (12079 states) and $R(F)$ (122 risk states) differ by two orders of magnitude. We believe, such an abstraction underpins the potential usefulness of the proposed risk model in such applications.

For RQ3, we can at the current stage of this project only provide a ballpark figure for the detection and handling overheads. Let $t: \alpha \rightarrow \mathbb{R}$ be the processing time required for an action, e.g. for the calculation of the detection of HC in $e^{HC}$. If implemented as part of a sequential cell controller, the ASC requires a time slot of length $\Sigma_{t \in F} t(e^f)$ in each control cycle. If monitored simultaneously in dedicated ASC hardware, the slowest detection rate for $F$ is $1/\max_{e \in F} t(e^f)$. The overhead for handling $f$ can be estimated from Fig. 6 and may range from $t(m_e^{HC})$ to $\Sigma_{k \in \{sm, a, sf\}} (t(m_k^f) + t(m_e^{HC}))$.

3To keep manual workload under control, if PRISM lists several adversaries, we apply the experiment procedure only to the first listed.
C. Discussion

Relative Safety of a Policy: To simplify game-theoretic reasoning about $M$, we reduce non-deterministic choice for the environment (i.e., operator, robot, welder). The more deterministic such choice, the closer the gap between policy space $\Pi_M$ and ASC design space. Any decisions left to the environment will make a verified policy $\pi$ safe relative to $\pi$’s environmental decisions. These decisions form the assumption of the ASC’s safety guarantee. Occupational health and safety assumes trained operators not to act maliciously, suggesting “friendly environments” with realistic human errors. To increase priority of the ASC, we can express such an assumption, e.g. by minimising risk and maximising pot.

Sensing Assumptions: In our example, the ASC relies on the detection of an operator (e.g. extremities, body) and a robot (e.g. arm, effector) entering a location, the cell state (e.g. grabber occupied, workbench support filled), and the workpiece location (e.g. in grabber, in support). For $M$, we assume the tracking system (i.e., range finder and light barrier in the industrial setting, Kinect in the lab replica) to map the location of the operator and robot to the areas “at table”, “at workbench”, “in cell”, and “at welding spot”. In Fig. 1b, the range finder signals “at welding spot” if the closest detected object is nearer than the close range, and “in cell” if the closest object is nearer than the wide range. Tracking extensions, not discussed here, could include object silhouettes and minimum distances, operator intent, or joint velocities and forces.

Sensor Faults: pGCL requires much care with the modelling of real-time behaviour, particularly, when actions from several concurrent modules are enabled. To model real-time ASC behaviour, we synchronise operator actions with sensor events and force the priority of ASC reactions in $\pi^*$ by maximising the risk reduction potential (cf. pot in Tab. III). While synchronisation restricts global variable use increasing $M$’s state space, we found it to be the best solution.

Model Debugging and Tool Restrictions: To reduce the state space, we strongly discretise location. To simplify debugging, we use probabilistic choice in synchronous updates only in one of the participating commands. To support synchronisation with complex updates, we avoid global variables.

State rewards would allow a natural modelling of, e.g. risk exposure. In PRISM 4.5, one needs to use action rewards for multi-objective queries of MDPs. Risk gradient matrices help to overcome a minor restriction in PRISM’s definition of action rewards. Otherwise, we could have introduced extra states, however, at the cost of increasing $M$’s state space, undesirable for synthesis. Rewards require the elimination of non-zero end components (i.e., deadlocks or components with cycles that allow infinite paths and, hence, infinite reward accumulation). PRISM provides facilities to identify such components, however, their elimination is non-trivial and laborious in large models and can require intricate model revisions.

VII. Conclusion

We introduced a tool-supported method for the correct-by-construction synthesis of automatic safety controllers from Markov decision process models of human-robot collaboration settings. These controllers implement regulatory safety goals for such settings. We describe steps for streamlining the modelling of MDPs. Our method draws support from two tools, YAP for structured risk modelling and MDP generation and PRISM for probabilistic model checking and MDP policy synthesis. We show that our approach can be used to incrementally build up multi-hazard models including alternative mitigation and resumption options. Hence, our approach improves the state of the art of ASC synthesis for HRC settings, particularly when dealing with multiple risks, mitigation options, and safety modes. The verification results obtained by using our method can form evidence in an ASC assurance case [29].

Future Work: Our approach limits the inference of high effectiveness of an ASC from high conditional accident freedom of the associated policy. Our setting can require the assessment of how much the decisions of the ASC and the environment contribute to the accident freedom. We plan to explore game-theoretic settings to remove this limitation.

The evaluation of the verified controller in the manufacturing cell (e.g. overhead in resource usage, influence on nominal operation) is out of scope of this paper. Such an evaluation requires the translation of the controller into an executable form. Our next steps will be the conversion of the synthesised
DTMC into a program for the digital twin simulator and the replica of the cell. Note that this translation has to be verified to match the executable form with the verified properties. Additionally, we plan to derive tests for this program from the facilities provided by the simulator.

For optimal synthesis, the proposed method uses parameters such as upper risk and severity bounds in constraints. We plan to introduce parameters for the probabilities into the MDP, supported by tools such as evoCHECKER [30], and to use parametric risk gradient matrices by extending Yap. We intend to explore the use of evoCHECKER to avoid the split of the verification procedure into two stages (cf. Secs. V-D2 and V-D4). We also like to explore online policy synthesis to allow more variety in environmental decisions (e.g. malicious operators). This corresponds to weakening the assumptions under which the ASC can guarantee safety.

Unable to collect data (cf. Sec. V-B) from an industrial application, we had to make best guesses of probabilities. However, the frequency of undesired intrusion of operators into the safeguarded area and accident likelihood can be transferred into our example. This example can be extended by randomised control decisions with fixed probabilities (e.g. workload), by adding uncertain action outcomes (e.g. welding errors), and by time-dependent randomised choice of mitigation options. To use time in guarded commands, we want to errors), and by time-dependent randomised choice of mitigation options. To use time in guarded commands, we want to under which the ASC can guarantee safety.

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