Risk Evaluation of Robot Soccer with Humans in RoboCup MSL

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1 Introduction

The RoboCup Middle-Size League (MSL) Technical Committee (TC) is in charge of the rulebook for the league. They publish a new rulebook yearly.

For RoboCup 2022, the MSL TC published the new rules on December 31st, 2021. The one rule change that stood out the most was to promote research regarding playing with humans, by allowing a single robot to be replaced by a human. Previously, playing with humans was only promoted through Technical and Scientific Challenges. Unfortunately, this did not yet result in much progress.

The rules specify a list of limitations to make the game safe (both for the human and the robots) and fair. These can be found in "COMPETITION RULE 7" in the MSL rulebook[1]. The limitations mostly focus on a fair game, rather than safety.

While and after publishing the new rulebook, the TC has been in contact with the RoboCup trustees to discuss how to also specify safety requirements. Several possibilities have been discussed, but no decisions have been made.

This document aims to provide an overview of the safety risks involved with replacing a robot in MSL by a human player and how the greatest safety risks can be mitigated.

1.1 Baselines

A set of baselines is identified around which the risk assessment will take place. Baselines can be related to existing mitigation measures, but are in this case focused on defining acceptable risks.

- We assume that the robots are allowed to participate in RoboCup MSL (i.e. they satisfy the existing rules).
- We consider the existing risk of the human referee and assistant referee to be acceptable.
- We consider the existing risk of having an audience besides the field to be acceptable.
- Risks similar to those commonly involved in traditional soccer or futsal are acceptable.
- Risks unrelated to the robot interaction (e.g. pulling a muscle) are not taken into account.
- Rules to ensure fair play should never compromise safety.

[1] `https://msl.robocup.org/wp-content/uploads/2022/01/Rulebook_MSL2022_v23.0.pdf`

1.2 Risk rating

We rate the risks in section 2 on two scales: First, the *probability* of a risk occurring is rated on a scale from 1 through 5. Secondly, the severity of the *consequence* when the risk occurs is also rated on a scale from 1 through 5.

The probability is rated as follows:

1. Unique. Unlikely to ever occur. No known occurrences in the history of RoboCup MSL.
2. Unlikely. Is not expected to occur, but is conceivable.
3. Infrequent. Could occur once in a tournament, but does not occur every tournament.
4. Regular. Is expected to occur multiple times in a tournament.
5. Common. Is expected to occur multiple times per match.

The consequence is rated as follows:

1. No consequence.
2. Slight discomfort (e.g. bruises).
3. Injuries similar to those common in human soccer or futsal.
4. Serious injury (e.g. broken bones).
5. Severe injury (generally associated with hospitalization).

The primary goal of this risk rating is to keep humans safe from harm. However, there is another important factor to take into account. Injuries caused by robots get more media attention than similar injuries in human soccer matches. We also see this in autonomous cars: serious accidents with autonomous cars are more often reported in the media than similar human accidents. Especially considering that accidents with autonomous cars are less frequent.

Final risk score is calculated by the product of the two scores. Final scores > 4 are subject to additional investigation, scores > 9 require rules to be mitigated. Table 1 shows this scoring system, including which scores are subject to further investigation and which scores require mitigation. A score of > 4 ensures that any risk with a probability or consequence at level 5 is evaluated, even if the other score is only rated at level 1. A score > 9 implies a combination of two non-negligible factors, most likely resulting in a risk that is not considered acceptable.

Table 1: Risk scores, cells highlighted in yellow require additional investigation, cells highlighted in red need rules to mitigate these risks.

		Probability				
		1	2	3	4	5
Consequence	1	1	2	3	4	5
	2	2	4	6	8	10
	3	3	6	9	12	15
	4	4	8	12	16	20
	5	5	10	15	20	25

2 Risks Evaluation

This section identifies a list of risks when people play soccer together with the MSL robots.

2.1 Robot driving into a person

2.1.1 At low speed

A robot bumping into a human. Similar to how humans may push an opponent to gain control over the ball.

Probability: 5/5. Bumping (also called *pushing* in MSL) occurs regularly. If it affects the game, the referee should step in.

Consequence: 1/5. The shins and feet of the human are the main body parts at risk. If those are properly protected, humans are not harmed by this.

Risk: 5/25.

2.1.2 At high speed

A robot driving at high speed (may be out of control) hits the human.

Probability: 4/5. It happens at every tournament that a team loses control of a robot. Generally, the consequence it that they hit the safety barrier, and get stopped there.

Consequence: 4/5. A robot of 40 kg at 4 m/s has a lot of energy to dissipate. When this happens to hit a human, broken bones are to be expected. A border of 1 cm is not sufficient (according to RC-4.1).

Risk: 16/25.

2.2 Tripping

2.2.1 Fallen human hit by robot

A human falls, but none of the robots can be identified as the cause. When they are on the ground, they are significantly more vulnerable. This risk evaluates the human encountering a robot when they are on the ground.

Probability: 2/5. Humans generally do not trip on their own, but this could happen. It is even less likely that a robot hits the human before the game is stopped by the referee.

Consequence: 4/5. The head and hands become significantly more vulnerable. When a robot ends up hitting the human, this is likely to require the human to be checked and, if necessary, treated in a hospital.

Risk: 8/25.

2.2.2 Over a robot

A human might overlook a robot, and consequently trip over it. An additional risk (over risk 2.2.1) is that the human falls onto the robot, or rests their hand for support to stay upright.

Probability: 3/5. While not likely to happen in every match, a human might be surprised by a robot in a moment of inattention, or be focused on something else and trip because of that.

Consequence: 3/5. Especially sharp parts of the robot may be a hazard for the human to get cut. When a human tries to support their fall by grabbing the robot, they may come in contact with electronics (risk 2.10) or a sharp edge (risk 2.5).

Risk: 9/25.

2.3 Shoot ball at human

A robot may shoot the ball when a human is in its way. This can also happen in normal soccer. Especially getting hit in the head/face is the risk here.

Probability: 2/5. There is no reason for the robot to hit the human in the head. It may still happen as an accident, but this also means the human did not see the ball coming (meaning they are not actively participating in the game, and did not dodge).

Consequence: 3/5. In most cases, it will just hurt. There may be rare, unfortunate cases where the ball does more damage (e.g. to a human's nose).

Risk: 6/25.

2.4 Get hit by the shooting mechanism

A human in a scrum situation with the robot may get their foot near the shooting mechanism. If the robot activates the shooting mechanism without the ball, it may hit the human's foot. If the ball is present, it will dissipate some of the energy, and the mechanism will not hit the human's foot.

Probability: 2/5. Although not impossible, it is very unlikely that the human's foot is near the shooting mechanism if the ball is not. Additionally, the robot would have to shoot while it does not have the ball, which is also unlikely to happen.

Consequence: 4/5. Likely leads to broken bones in the human's foot.

Risk: 8/25.

2.5 Get hit by a sharp corner/edge

The rules generally say that the robots must be 'safe', but do not explicitly forbid sharp corners or edges. An interaction between a human and robot may lead to the human being cut.

Probability: 3/5. Requires an unlucky interaction between the human and robot.

Consequence: 3/5. May cause blood to be drawn. Unless edges are purposefully sharp, unlikely to cause any more significant injury.

Risk: 9/25.

2.6 Flying parts

2.6.1 High speed/heavy (high kinetic energy)

A heavy part becomes disconnected from the robot, or a part becomes disconnected at high speed. Think for example of (part of) the shooting mechanism.

Probability: 1/5. Has not been seen ever before.

Consequence: 5/5. If the part hits the human in an unlucky manner, can cause severe injury.

Risk: 5/25.

2.6.2 Low speed/lightweight (low kinetic energy)

For example, a robot marker becomes detached.

Probability: 4/5. A robot marker coming off is a relatively common occurance, and happens several times every tournament.

Consequence: 1/5. No risk of injury.

Risk: 4/25.

2.7 Driving over foot

A robot drives over the foot of a human.

Probability: 1/5. The (current) MSL robots do not have sufficient clearance to drive over a foot.

Consequence: 3/5. Assuming the human is wearing proper footware (closed toed, firm), severity of injury is limited.

Risk: 3/25.

2.8 Human scared that they are undetected

When the human is not sure if the robot has detected them (e.g. because the robots drive fast near the human), they will constantly be looking out for their own safety. This means they can not properly participate in the match.

Probability: 4/5. Especially early on, in the first tournaments, this is a reasonable worry of the human player. As experience is gained by humans and robots, confidence in safety will increase.

Consequence: 1/5. A possible consequence is risk 2.1.2. Although, just because the human is scared, does not mean they are in any actual danger.

Risk: 4/25.

2.9 Team does not handle stop signal

When the stop signal is issued by the RefBox, teams should ensure that their robots stop moving. Sometimes this does not happen (whether this is because of a loss of WiFi signal, being disconnected from the RefBox, or a software bug is irrelevant).

Probability: 3/5. This happens at tournaments, but is not a common occurance.

Consequence: 4/5. The risk of being hit (2.1.1, 2.1.2) is the most likely. We score this according to the worst case.

Risk: 12/25.

2.10 High voltage/current

The risk of exposed electronics for a human who is not familiar with the risks of the specific robot.

Probability: 2/5. Not all teams may have properly protected the (high voltage) electronics of their robot.

Consequence: 5/5. Depending on the amount of current and voltage, this may seriously harm the human.

Risk: 10/25.

2.11 Hot components

The risk when some parts of the robots reach a temperature where they can burn or hurt a human, when they touch this component. We set this limit to be any temperature $> 40^\circ$C.

Probability: 3/5. There are two parts to this probability. Firstly, whether components reach this temperature. This will most likely occur continuously on some parts. Secondly, the probability that the human will actually touch this component. This is mostly dependent on the design of the teams.
It is likely that humans touch the robots, this may also happen regularly. If they are unlucky, which we consider unlikely, this component is hot.

Consequence: 4/5. Depending on the exact temperature, a human may burnt severely by touching components that are hot.

Risk: 12/25.

3 Risk Mitigation

This section proposes possible mitigation techniques for the most important risks of the previous section. We distinguish three ways to mitigate risks, for those that require mitigation:

- **By design:** The fundamental design of the robot is changed such that the risk is reduced to a level where the risk is considered acceptable.
- **Safety measures:** The fundamental risk remains the same, but measures are introduced to reduce the actual probability or consequence.
- **Notification:** Mitigate the risk by informing the people of possible risks (e.g. through a handbook, or warning stickers).

3.1 Robot driving into a person

3.1.1 At low speed

Safety measure: The first version of rules specifies that the human must wear protective gear on their feet and lower legs. This is sufficient protection from a low speed robot pushing a human.

3.1.2 At high speed

Safety measure: A high speed robot has a lot of energy to dissipate. Ideally, the human jumps out of the way, if this does not happen the time over which the energy is dissipated needs to be extended. A possibility is to lower the maximum speed or mass of the robots, or add a thick foam layer around the robots[2].

3.2 Tripping

3.2.1 Fallen human hit by robot

Safety measure: The probability of this happening is small, ideally the possible consequence is reduced. Gloves and protective head-ware (that remains on one's head after tripping) would achieve this.

3.2.2 Over a robot

Reducing the probability is difficult, as the main identified cause is human inattention. The consequences are reduced in 3.5 and 3.10.

[2] The force exerted on the human is proportional to the duration of the impact ($F = \frac{m_{robot} \cdot v_{robot}}{t_{impact}}$), a thicker foam layer increases this duration.

3.3 Shoot ball at human

The small probability where the consequence is worse than a little pain, such as getting hit in the nose, could be fully mitigated by protective headwear.

3.4 Get hit by the shooting mechanism

Safety measure: According to the existing rules, the human is not allowed to obtain the ball directly from the robot's ball handling mechanism. If additionally the robot is not allowed to intercept the ball when the human has ball possession, this risk cannot occur.

3.5 Get hit by a sharp corner/edge

By design: The easiest way is to add a technical requirement that all sharp edges on robots need to be protected. The MSL TC can ensure teams do this properly during the technical validation.

3.6 Flying parts

3.6.1 High speed/heavy (high kinetic energy)

Referees and audience are at the same risk currently, and we have defined this risk to be acceptable.

3.6.2 Low speed/lightweight (low kinetic energy)

No further investigation necessary.

3.7 Driving over foot

No further investigation necessary.

3.8 Human scared that they are undetected

No further investigation necessary. If there is an actual risk, this is handled in the other sections.

3.9 Team does not handle stop signal

Safety measure: The rules already specify that the referee can refuse a human player in a game when they deem it unsafe. If a team does not (instantly) process the stop signal, the referee can decide to remove current/refuse future humans in the game.

Safety measure: Additionally, teams already need to have an emergency stop (RC-4.1), which may be used if the robots do not stop after a RefBox signal.

3.10 High voltage/current

By design: An additional rule to satisfy ensuring high voltage safety may be introduced. The easiest way to do this, is to refer the teams to an existing machine safety standard requiring teams to ensure proper shielding.

3.11 Hot components

Safety measure: The easiest way to resolve this, is to shield components that are expected to exceed $> 40°C$ during normal operation. Requiring shielding satisfying IP2X[3] is effective protection for fingers and larger limbs. Official certification should not be necessary.

[3]For details on the Ingress Protection Code see IEC 60529 or EN 60529.

4 Rule proposals

The rules already specify a list of requirements to achieve a fair and safe game. Based on the risk analysis and mitigation, the following changes and additions are proposed.

1. Change the existing rule *"The human can only move at most at walking speed."* into "The human may not *get an unfair advantage* through moving faster than walking speed". Additionally, specify that the human may not *get an unfair advantage* by moving when in possession of the ball.
   Both changes are intended to allow a human to ensure their own safety, the definition of "an unfair advantage" would need to be defined by the referee on a per-case basis.

2. Change that the footwear needs to be solid (besides closed up to the ankle, and without spikes).

3. Change *"Human can only obtain the ball through a pass, or when it's not in possession of any robot."* into *"The ball can only change ownership between a human and a robot through a pass, or when it is rolling freely."* to prevent scrum situations between robot and human.

4. Add a requirement for a larger foam coating to absorb energy on a high speed collision. Of course, the size of this foam layer should not reduce the size to build the robot available to the teams.

5. Add a requirement to protect all sharp edges and corners.

6. Add a requirement to properly protect the electronics (for example, satisfying a standard by the NIST EEEL (National Institute of Standards and Technology, Electronics and Electrical Engineering Laboratory) [4]).

7. Add a requirement where any component expected to reach a temperature $> 40°C$ should be shielded satisfying IP2X. Official certification is not required.

8. Add a requirement for the human to wear protective gloves.

9. Add a requirement for the human to wear protective head-wear that stays on after a fall.

10. Remove the requirement that the humans can only move between the height of the two penalty markers. (The MSL TC decided on this rule, but it was misplaced in the publication version).

Additionally, one may consider to impose additional restrictions the first time (e.g. in a test event) when robots play together with humans. However, given the risk assessment, we would only recommend these if there are concrete safety

[4] https://www.nist.gov/system/files/documents/el/isd/mmc/high_voltage_rules_revised.pdf

concerns that cannot be mitigated using other measures. We mention two possibilities:

1. Identify a fixed area where the human is located, and the robot is not allowed to enter. This should reduce the chance of any collisions, as discussed previously by the TC.

2. Use remote controlled ‘humans’ (e.g. mannequins) to stand in for humans. This allows teams to test their human-recognition software without the risk of hitting a real human in case it does not work perfectly.