Critical Point Combat robotics

TV robot fights are not just entertainment – they can also help turn students on to physics and engineering, as **Robert P Crease** finds out

Daniel Longmire

Heavyweight champ The team behind fighting robot MadCatter, headed by physicist Martin Mason (right).

The two 110 kg combat robots squared off. One, known as Poison Arrow, was armed with a toothed spinning drum. Its adversary, Son of Wyachi (SOW), had whirling hammers. Poison Arrow smashed into SOW, sending it flying across the arena. SOW broke its radio receiver as it crash-landed, lying motionless as the referee declared a knockout (bit.ly/2Rcgjhy).

The action took place in 2016 in *BattleBots* – a US "robot-combat" TV series aired by ABC in 2015–2016, and then by the Discovery Channel since 2018. *BattleBots* is inspired by the original Robot Wars events held in the US in the 1990s; these events also inspired the famed British TV series *Robot Wars*. Dubbed "the ultimate robot-fighting competition", *BattleBots* features fights to the finish between remote-controlled "bots" that employ an array of destructive weapons.

Roared on by a crowd, the robots compete in physical bouts, divided – just as in boxing or wrestling – into different weight classes. While the sport at large features everything from fairyweight to heavyweight contests, *BattleBots* only involves heavyweight fighters. The 2016 scrap between Poison Arrow and SOW has been judged one of the most dramatic knockouts in *BattleBots* history.

Many colleges and universities in the US now have teams that compete in the smaller weight-class events – not just because these are held more often and in more places but also because they work well as teaching projects, extracurricular activities and an entry into the sport. *BattleBots*, though, has an international appeal, with notable British robots to have appeared on the show including Quantum, Bet and Monsoon (developed by engineers in Birmingham, Surrey and Bedfordshire, respectively).

One of Poison Arrow's designers is Casey Kuhns, an avionics engineer at Ursa Major Technologies in Colorado who originally studied physics. As he explained to me over the phone, there's much more to *BattleBots* than just spectacular crashes. Designing robots, he believes, is a terrific hook for engaging students and teaching them physics. "We all study the pool ball thing," he says, pondering Newtonian mechanics using collisions of pool balls, "but here's a chance to study larger applications."

Awed spectators to the event told Kuhns that they thought that SOW had flown up to 5 m high before crashing. To check if the audience was right, Poison Arrow's team members analysed their robot's fight frame by frame, showing that its opponent had spent 1.1 seconds aloft. Using elementary Newtonian physics, they then calculated its trajectory – finding that however awesome the crash looked, their robot had kicked its adversary 5 m horizontally but only 1.5 m vertically (bit.ly/3cDXig6).

Poison Arrow's creators had, in other words, turned a dramatic encounter between two robots on TV into a "teaching moment" that illustrates simple physics in a fun and accessible way. They also showed how to calculate the energy transfer of the collision, and pointed out that the reason SOW hadn't tumbled in flight but flew flat like a drone was the gyroscopic stability provided by its spinning hammer.

One key physics principle in combat robotics is rotational inertia. Or, as Kuhns puts it: "How do you balance spinning a weapon and maintaining stability while driving?" Weapons bearings are another issue. Poison Arrow's drum weighs 32 kg and spins at 9000 revolutions per minute – so how much force, Kuhns asks, can you apply to its bearings before it fails? Electronics plays its part too. "You've got high-powered motors in a small setting, lots of emf, and you have to think carefully about what sensors you use and how to route things."

Poison Arrow's other team members, who included Zach Goff, director of engineering at L&L Fabrication in Colorado, even developed a calculator to show how long it takes a spinning weapon to ramp up to its maximum allowable tip speed of 250 miles per hour, and to determine kinetic energy, energy draw and other properties. Kuhns and Goff still haven't figured out how to estimate the aerodynamic drag of a flywheel, which appears to make their calculations underestimate data at higher speeds, and would welcome assistance from *Physics World* readers.

Cut-throat cat

In one of the most astonishing bouts of the most recent season, MadCatter was low to the ground and painted to look like a cat, with its tail a hammer with a flamethrower. It inched towards Malice, whose weapon was a 65 pound (30 kg) horizontal spinning disc. MadCatter struck Malice, flipping it over in a shower of sparks and flame. A few seconds later, MadCatter struck again and Malice spun away wildly. MadCatter struck a third time, clipping Malice's left wheel and knocking it on its back. Something extraordinary then happened.

Malice remained fully functional on its back, but was unable to rock itself over thanks to the rotational momentum of its disc, which was now spinning like the wheel of an upside-down bicycle. Malice had wound up in a stable configuration that its designers knew about but hadn't thought to guard against, because the chances were so freakish of encountering just the right combination of forces to put it there. As the referee counted down a KO, MadCatter sat with its two eyes gazing with astonishment at the hapless Malice (bit.ly/3rEGXfr).

The two match announcers also gaped, having never seen anything like it either.

"It's physics, Chris," the one said to the other, by way of explanation.

Martin Mason, a physicist and head of the MadCatter team, is as much fun to watch as the matches themselves. Like a pro wrestling champion, he'll adopt an aggressive persona to gee up the audience and inspire people to tune in. Eyes bulging, eyebrows raised, pointing his finger directly at the camera, he'll shout in a deep gravelly voice something like: "I'm going to pulverize you!" When I phoned Mason in California, I said I was glad to be safely on the other side of the country from him.

Turns out he's really friendly and all he means is that his robot is about to pulverize yours, which is nearly always true. Mason's day job is as challenging as robotics. He's just one of a handful of physics professors in the engineering department at Mt San Antonio Community College, just outside Los Angeles, which serves about 50 000 mostly minority and lower-income students. Mason uses robotics to get those students to devise models that can be implemented in a short time in vastly different contexts.

"When I studied physics in graduate school I spent a lot of time at the computer," Mason told me. "Here I have to be concrete, practical and engage students quickly." Robotics also enables him to teach students how to make the most of limited resources. "We know we are not going to have the best motors and the best materials, but we want to have the robot run at 100% of what it can do." Mason's team finds, for instance, that maximizing a robot's "punch" can be less important than drivability – the ability to immediately recover from contact and come back to hit the opponent again.

Non-mortal combat Two legendary *BattleBots* fights: Poison Arrow vs SOW (left) and Minotaur vs Blacksmith.

The bull

One of the most exciting and legendary battles in combat robotics, also on the 2016 season of *BattleBots*, featured Minotaur and Blacksmith. They began by circling each other warily. Blacksmith then suddenly slammed Minotaur into the railing, but Minotaur rallied and crushed its spinning drum into Blacksmith's flank, sending it flying amid showers of sparks. Landing upside down, Blacksmith righted itself and pounded Minotaur with its 8 kg hammer, momentarily stopping Minotaur's drum.

Restarting its weapon, Minotaur then ground off Blacksmith's wedge, knocked off the head of its hammer, and pulverized Blacksmith until its motor exploded. Smoke and flames billowed from Blacksmith, which flapped the shaft of its hammer helplessly. As the referee counted down, Minotaur began gyrodancing, tilting itself onto one wheel and spinning in celebratory circles. The fight has so far been viewed nearly 20 million times on YouTube alone (bit.ly/3fMzhFU).

Minotaur was designed by Marco Meggiolaro, a mechanical engineer at the Pontifical Catholic University of Rio de Janeiro in Brazil. Meggiolaro has written extensively about the physics of combat robotics, and published *Riobotz Robot Combat Tutorial* – the most up-to-date textbook on the subject (bit.ly/31Q21Fo). Minotaur was a class project, and its team is composed of Meggiolaro's current and former students.

He told me that the basic physics of combat robotics – energy storage and transfer – is simple. But incorporating those principles into massive, radio-controlled vehicles that can attack and defend successfully in duels against similar adversaries with an array of different weapons gave him enough educational material for entire courses in physics and engineering. Even a combat robot's drive system alone poses complex physics issues, Meggiolaro explained.

You need good acceleration, for example, so that you can reverse direction to dodge and get behind opponents. Gear ratio is vital too to propel a stationary robot to the other side of the arena in under two seconds. Also important is torque – what allowed Minotaur its victory dance – while motors and batteries have to be carefully designed. Minotaur draws 800 A of current in each motor, using brush motors for the drive, and brushless motors for the weapon. "We burn up a lot of motors," Meggiolaro admits.

Minotaur's weapon poses especially difficult physics problems. Consisting of a toothed drum designed to launch an opponent or rip off its armour, its key parameters are inertia, strength, number and height of the teeth, rotational speed, collision speed and "tooth bite". This parameter, which is the overlap between the weapon and the opponent, depends on the number of teeth, the angular velocity of the weapon and the relative speed of the two robots.

Lots of small teeth on a drum will chew away at the opponent like a wood chipper, but that takes too much time and causes little damage. Fewer teeth, on the other hand, will provide an uppercut that transfers lots of energy. A single-toothed drum has greater tooth bite but requires a counterweight; two symmetrically placed teeth make the drum more balanced but provide less tooth bite. One good counterweight material is a tungsten alloy so expensive that Meggiolaro explored asymmetrical shapes to eliminate the need for counterweights.

The critical point

The televised broadcast of these fights is riveting, but I'm told it is even more thrilling in person, and not just because of the deafening screams of the spectators. In person at *BattleBots* you hear the uncanny sounds of the combatants – the scraping and grating of metal, the motors groaning under suddenly elevated loads, the crackle of sparks, the occasional bursting of the machines into flames, and the drama of seeing 110 kg robots send each other spinning several metres in the air, crash upside down on the ground, right themselves, and then turn and attack each other as handily if they were heavily armoured cats.

In the first few seasons of *BattleBots*, one effective strategy for competitors was simply to build a robot that was reliable enough to survive in the ring, in the hope that the rival robot would fail, whether by blowing a motor, breaking a drive chain, cracking the chassis or perhaps losing its weapon. After five seasons of engineering trial and error, however, effective strategies rely more and more on physics. Competitors need to inventively incorporate things like bite, energy transfer and absorption, torque and voltage, making the competition ever more effective as tool to learn and study physics.

At a time when robots, computers and other mechanical devices are forcing us to reconsider what it means to think, pitting robots against each other is, in turn, forcing us to think about physics with a fresh perspective.

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