Virtual Robots RoboCupRescue Competition: Contributions to Infrastructure and Science

Michael Lewis
School of Information

Sciences
University of Pittsburgh
ml@sis.pitt.edu

Stefano Carpin
School of Engineering

University of California, Merced
scarpin@eng.umerced.edu

Stephen Balakirsky
Intelligent Systems Division
National Institute of Standards and Technology
stephen@nist.gov

Abstract

The Virtual Robots (VR) competition using the USARSim simulator began in 2006 in Bremen as a parallel activity of teams actively competing in Rescue Robot competitions. The competition has benefited the robotics research community by accelerating the development of and maintaining research infrastructure (USARSim) and by focusing competitions on issues meaningful to research including multirobot control and mapping. Research users of the simulation are evenly divided between those who do and those who do not participate in the competition, demonstrating that its benefits have not been limited to an overly narrow problem or "playing to the rules."

1 Introduction

Since its inclusion into RoboCup in 2001, "RoboCup Rescue has been structured in two leagues, the Rescue Robot League and the Rescue Simulation League. The Virtual Robot competition was added to the Rescue Simulation League in 2006 and falls somewhere between the existing competitions. Whereas the Rescue Robot League [Jacoff et al., 2001] fosters the development of high-mobility platforms with adequate sensing capabilities to identify human bodies under harsh conditions, the original Rescue Simulation competition promoted research in planning, learning, and information exchange for an inherently distributed rescue effort [Kitano and Tadokoro, 2001]. The simulation used by the RoboCup Rescue Simulation competition is a multiagent simulation representing entities such as firefighter units, ambulances, and police units that are managed and deployed in a Federal Emergency Management Agency (FEMA) level resource management and dispatching task.

The Rescue Robot League grew out of an initiative at the National Institute of Standards and Technology (NIST) to develop standard reference test environments to assess the capabilities of rescue robots. Competition in the NIST arenas began in 2000 at the annual meeting of the Association for Advancement of Artificial Intelligence (AAAI) in Austin, Texas. The following year at the AAAI meeting in Chicago it became a competition within RoboCup. In the early years of the competition standard academic research platforms predominated. But by 2005, with the introduction of step fields and the increasing premium the rules placed on advanced mobility, only teams developing hardware specifically for the competition/rescue applications or purchasing specialized platforms remained competitive. First place that year, for example, went to Toin Pelican, with a custom developed Japanese rescue robot with 2nd and 3rd places going to teams relying on the $100,000+ commercial DT-3 robot.

The Virtual Robots (VR) competition using the USARSim simulator began in 2006 in Bremen as a parallel activity of teams actively competing in Rescue Robot competitions. Virtual Robots became the third competition held within the RobocupRescue Simulation league. The scientific goal of Virtual Robots is to provide a testing scenario where teams are called upon to perform rescue missions requiring multiple cooperating heterogeneous robots operating both inside and outside of a disaster area of the size of a few city blocks. Both autonomy and teleoperation are accepted and rewarded by the scoring schema [Balakirsky et al., 2007, Carpin et al. 2006, Carpin et al., 2007]. Figure 1 shows one of the competition worlds used during the competition held in Bremen in 2006. The scenario portrayed an explosion happening in a building located at the intersection of four major roads. Rescue missions took place both inside and outside the building. In 2007 and 2008, the scenario consisted of a major train wreck occurring within a train station with a subsequent chemical spill and fire involving nearby office buildings (short videos of these environments are available on [Merced, 2009].

The goal of a competing team is to explore and map the unknown area and to report as much information as possible to a hypothetical team of first responders that have to enter the area to rescue victims. Relevant information includes the map of the environment, location of the victims, and classification of the explored terrain (victim free, unknown, etc). After three successful events, notable progress in cooperation, human robot interfaces, and adjustable autonomy have been observed. By raising the bar every year, the organizing technical committee has forced teams to develop new skills, and has also brought new extensions to USARsim. For example, starting from 2007, teams have been forced to use a so-called wireless simulation server (WSS) in order to exchange information between robots and the GUI during the competition. In 2008, flying vehicles with limited sensor payload were introduced and significantly wider competiti

Figure 1: USARSim is the simulation engine used to run the RobocupRescue Virtual Robots competition. The picture shows one of the environments used during Robocup 2006. A tracked Telemax robot and a flying AirRobot platform can be seen in the screenshot.

tion scenarios were presented to the teams in order to encourage them to use cooperative heterogeneous teams including the newly introduced air platform. It is important to remark that all participants in the Virtual Robots competition are required to release their code to the community in order to lower entry barriers for new comers. This may be seen in the fact that the winner of the 2008 competition (RedSun from Southeast University, Nanjing, China) based their code on the 2007 wining code (Steel of Pittsburgh/CMU). Moreover, some of the scoring tools initially adopted within the Virtual Robots competition have also been embraced by the RobocupRescue Robot league, thus closing the loop between simulation and reality.

Since its inception the VR Rescue competition has emphasized validation of robot and sensor models with validation of information extracted from synthetic video [Carpin et al., 2006b], validation of the Hokuyu laser range finder model [Carpin et al., 2005] and extensive validations of platform performance for both standard [Lewis et al., 2005, Taylor, et al., 2007, Zaratti et al., 2006, Greggio et al., 2007, Okamoto et al., 2008] and experimental [Lewis et al., 2005, Pepper et al., 2007, Albrecht et al., 2006, Okamoto et al., 2007] platforms used in Rescue Robot competition. This emphasis on validation and fidelity and tie-in with Rescue Robots has allowed some teams [Carpin et al., 2007, Albrecht et al., 2006] to develop and test in simulation before porting directly to the modeled robots. More commonly the VR competition has allowed teams to develop and evaluate approaches to multirobot search, mapping, and control that would be impractical in the NIST arenas due to difficulties with 802.11 communications in overcrowded competition environments and the small size and mobility demands of the arenas. The VR competition which began with a 3 team demonstration in Osaka in 2005 has grown to a field of 16 qualified teams from 9 countries in this year's RoboCup to be held in Graz, Austria.

2 USARSim

"USARSim", originally stood for "urban search and rescue simulation" but has since been repositioned as "Unified System for Automation and Robot Simulation" to reflect its extension to other domains such as the IEEE/NIST Virtual Manufacturing Automation Competition. USARSim was originally developed as a high fidelity simulation of urban search and rescue (USAR) robots and environments and originally intended as a research tool for the study of human-robot interaction (HRI) and multi-robot coordination. USARSim uses Epic Games' UnrealEngine2 to provide a high fidelity simulator at low cost (currently less than 10$). USARSim supports HRI by accurately rendering user interface elements (particularly camera video), accurately representing robot automation and behavior, and accurately representing the remote environment that links the operator's awareness with the robot's behaviors. The current version of USARSim consists of models of standardized disaster environments, models of commercial and experimental robots, and sensor models. USARSim also provides users with the capability of building their own environments and robots. Its socket-based control API was designed to allow users to test their own control algorithms and user interfaces without additional programming. USARSim currently includes detailed models of the NIST Reference Test Arenas for Autonomous Mobile Robots (Jacoff et al. 2001) including a replica of the fixed Nike site, RoboCup soccer stadiums, the Atlanta motor speedway, a portion of the Chesapeake Bay, MD, and large buildings and outdoor environments used in the last three years of RoboCup competition. The current release of USARSim currently provides detailed models of twenty robots including such widely used research and commercial platforms as the Pioneer P2AT and P2DX, iRobot ATRV-Jr, Sony QRIO and Aibo, Foster-Miller Talon, and Rheinmetall Defence's Telemax. These models were constructed using the Karma physics engine (Karma 2002), a rigid body simulation that computes physical interactions in realtime. The scenes viewed from the simulated camera are acquired through a spectator, a special kind of disembodied player attached to the robot. Images are captured from video memory and stored in raw or jpeg format on an image server making synthetic video accessible to computer vision algorithms and allowing researchers to tune the properties of the camera, by specifying the desired frame rate, image format, noise, and/or post processing needed to match the camera being simulated.

2.1 VR Rescue, USARSim, and Contributions to Research Infrastructure

Work on USARSim was begun at the University of Pittsburgh and Carnegie Mellon University in late 2002 under an NSF ITR grant to study Robot, Agent, Person (RAP) teams in Urban Search And Rescue (USAR). The original intention was to use the simulation to develop and test coordination algorithms for the NIST arenas more rapidly and for more robots. After other groups expressed interest in an early version that was inseparably linked to the RETSINA [Sycara et al., 1996] multiagent infrastructure we re-wrote USARSim to allow users to connect to the robots directly or through middleware such as Player [Gerkey et al., 2003], Pyro [Blank et al., 2004], or MOAST [Balakirsky et al., 2005]. Throughout 2004 the simulation was available from a server at the University of Pittsburgh and maintained on a time available basis. The level of maintenance and support, however, was insufficient to satisfy users and the effort interfered with ongoing research at the lab.

The RoboCup Federation's approval of the VR Rescue competition following the 2004 demonstration in Osaka provided access to a broader base of support. The association of USARSim with the competition led to moving the simulation to SourceForge that with assistance from NIST. Over the next half year this involvement helped resolve many issues. Measurement units and conventions were standardized and documented. Platform/function specific behaviors and parameters were reorganized in a consistent fashion into mission packages. Extensive documentation and validation efforts including replications in simulation of Galileo's leaning tower experiments [Zaratti, 2006] were conducted to provide a firmer basis for simulation and generalization. Today there are more than 33 official developers with many other incidental contributors from around the world contributing to a simulation that has had more than 45,000 downloads. This intensive level of development and documentation has made USARSim substantially more valuable as infrastructure for research as well as expanding the community of VR competitors.

From the beginning USARSim has had dual roles as research infrastructure and a simulator for the VR Rescue competition. It was used by the developers at the University of Pittsburgh for a series of HRI studies of attitude display [Lewis et al., 2003] and camera use [Hughes et al., 2003] in 2003 and by the next year was already being used by other HRI groups studying ecological interface design [Nielsen and Goodrich, 2006], remote perception and path complexity [Phillips et al., 2005], and multiple robot interfaces [Humphrey et al., 2006]. With the acceptance of the VR Rescue competition use of USARSim in research spread to the broader robotics community. Many of these users have no direct connection with the VR Rescue competition.

It is not surprising given the simulation's strengths in synthetic video and realistic interactions that USARSim has frequently been used to study user interface issues. Studies exploiting the image server's ability to store split images have examined novel wide field multi-camera displays for snake robots [Midorikawa et al., 2008], picture-in-picture formats for multirobot control [Pittman et al., 2007], as well as more conventional omnidirectional displays [Roebert et al., 2008]. Ecological displays presenting camera views in the context of other sensor data have been explored by [Phillips et al., 2005, Nielsen and Goodrich, 2006, Nielsen et al., 2007, Lewis et al., 2003, Wang and Lewis, 2004, Lewis and Wang, 2007] along with studies of camera control [Hughes et al., 2003, Hughes and Lewis, 2004a,b, Hughes and Lewis, 2005a,b], conventional controllers [Chuan et al., 2008], and even control based on manipulation of stigmergy [Steele and Thomas, 2007]. One project [Schulenburg et al., 2007] has used the simulation end-to-end to prototype and design a robotic assistant for use in a medical laboratory.

Several groups [Olney, 2007, Harris and Rudnicky, 2007] have used USARSim as a convenient low maintenance environment for studying dialog management for robots. Others have found it a useful environment for studying machine learning [Cherubini et al., 2007, Cherubini et al., 2008, Kobayashi et al., 2008] or testing [Kensuke et al., 2008] of control algorithms. USARSim has again been used by multiple groups [Schlenoff et al., 2007, Ng et al., 2007] to model and investigate driving behaviors. Some of the more idiosyncratic uses have included models of social interaction [Wagner, 2008], service composition for robots [Yachir et al., 2008], and studies of self diagnosis for navigation [Kleiner et al., 2008].

Other lines of research can be more closely associated with the goals and development for the VR Rescue competition. An initial goal for both the simulation and the VR Competition was the study of multirobot coordination and control. A cursory search finds groups active in the competition [Visser and Slamet, 2008a,b, Ziparo et al., 2007, Markov and Carpin, 2007, Wang et al., 2008a,b, Velagapudi et al., 2008, Wang and Lewis, 2007a,b, Wang et al., 2006a,b] and non-competitors [Nielsen and Goodrich, 2006, Nielsen et al., 2007, Humphrey et al., 2006, Humphrey et al., 2007] both making extensive use of the simulation for this purpose. The topics of study are not easily distinguishable between these groups and research of the VR competitors does not appear to be narrowly focused on issues arising in the competition.

2.2 Theses & Projects

Theses using USARSim follow a similar pattern dividing evenly between groups involved with the VR Rescue competition and non competitors. Thesis research topics have ranged from target tracking [Ethembabaoglu, 2007], modeling an omni dimensional camera [Schmits, 2008], to assessing coordination demand [Wang, 2007] for competitors. Other users have investigated the role of episodic memory in behavior [Endo, 2008], social interaction [Wagner, 2008], interface evaluation [Pina et al., 2008], and viewpoint control [Hughes, 2005]. USARSim is also being used on a number of DoD projects including Multidisciplinary Research Initiatives (MURIs) from Carnegie Mellon University, MIT, and UC Berkeley, a Science of Autonomy grant from ONR, and DARPA's SyNAPSE program.

3 VR Rescue, Mapping, and Contributions to Research

Contestants in the VR Rescue competition must search a wide area, build a map as they search, and mark the victims they discover on that map. Team scores are based primarily on the victims found and the accuracy and "usefulness" of their maps. The emphasis these rules have placed on multi-robot mapping for the contestants and evaluation of map quality for the organizers has led to focused research on these problems within the VR Rescue community. While early results from this work have been reported primarily at Robocup Symposia [Pfingsthorn et al., 2008, Sun et al., 2008, Varsadan et al., 2008] and workshops on rescue robotics [Sakenas et al., 2007, Iocchi et al., 2007] recent special sessions on mapping and map quality at PerMIS'08 and RSS'08 workshops and an upcoming special issue of the Autonomous Robots Journal promise to bring this work into the mainstream as an identifiable contribution of the VR Rescue competition.

4 Elemental tests, performance evaluation & repeatability

One of the manifest desiderata while administering a competition like Robocup is the implementation of objective scoring metrics not relying on any human intervention. This long term goal has not yet been achieved in the Virtual Robots competition, but has stimulated a lively discussion in order to converge to: a) a set of meaningful challenges aimed to outline the ability to achieve focused levels of competence; b) a set of open source tools to automatically score teams' performances. Needless to say, these challenges, called elemental tests in Robocup, are task dependent, but the idea can be easily generalized to other robotic problems. Experience in the Virtual Robots competition has shown that end-to-end performance measurements are not only hard to automate, but sometimes suboptimal by design. For example, ranking teams only on the basis of the overall score throughout a lengthy rescue mission has a clear bias to reward teams developing solid but simple implementations more than teams introducing novel ideas at the cost of increased software instability – an obvious price to pay while developing new designs. In competitions where the final result is established on the basis of few runs, a single failure is likely to lead to huge penalties in the final ranking, so teams will be less inclined to embark in high-risk high-payoff approaches. It has been observed that often times the winner is the team with the strongest weakest link in the overall architecture. While stability is a manifestly important element, it is not the ultimate and only valuable aspect to reward. Elemental tests were introduced in Robocup 2007 and reinvigorated for the 2009 competition. They aim to isolate simple tasks, so that system integration issues can be marginalized. For example, in the 2009 competition teams will face three elemental tests during the preliminary rounds, namely 1) the automatic deployment of a communication infrastructure to convey information outside the disaster area; 2) a teleoperation test where a single operator is asked to quickly guide numerous heterogeneous robots to a variety of locations; 3) a mapping challenge where the goal is to produce occupancy grid maps suitable for running a given path planning algorithm. It is clear that these entire components are instrumental in order to develop a useful USAR system capable of completing complex missions. However, by evaluating these elements separately it will be possible to identify inspiring solutions to these subproblems that may perhaps not emerge in the end-to-end final missions.

Equally important is the fact that automatic scoring tools have been developed for these tests, and have been made available to the scientific community. While the quest for a comprehensive scoring program capable to evaluate lengthy USAR missions is far from being over, these elemental tests can be automatically scored with a limited effort. Henceforth, teams will be able to numerically self assess their progresses as they introduce new features in their control code. More importantly, we have created a framework where best-in-class solutions for these elemental tests can be objectively established. Given that robotics is a discipline where repeatability is hard to achieve for crystal clear reasons, the introduction of these elements will hopefully offer researchers a way to contrast their findings against the state of the art in a more principled way. If this approach is embraced, it will be notably easier to assess limited improvements from major breakthroughs. This methodology is likely to be extendible to other domains, and would hopefully lead to a culture where before one embarks in proposing a new solution to the scientific community only after it is demonstrated to be measurably (and objectively) better than the state of the art.

5 Interactions Among Rules, Research, and Science

The scientific benefit to be gained from a research competition is strongly influenced by the rules in place. After a few stutters in the first year reported by [Thornburg and Thomas, 2007] the VR Rescue competition appears to have settled into rules that challenge competitors without fostering competition-specific solutions. The rules for the VR Rescue competition have been loosely modeled after those of the Rescue Robot League but with sufficient leeway to encourage progress on problems that could not be pursued in the physical league. In the first year described from four team's perspectives in [Balakirsky et al., 2007], following Rescue Robot rules, the scores of teams employing human operators were divided by $(1 + \text{N operators})^2$. Victims were provided with simulated RFID tags to allow autonomous detection at a substantial distance. Although these rules were intended to level the playing field by encouraging autonomy, they had the effect of rendering teams with human-in-the-loop approaches uncompetitive. Following the lead of the Rescue Robot League who had surreptitiously changed their scoring function the year before, the penalty for a single operator was removed for 2007. By 2008 the pendulum appears to have swung in the opposite direction with 1st place going to a teleoperated team. On other fronts the organizing committee has moved to progressively more difficult maps, introduced a communications server to limit bandwidth in communicating with robots and guided the competition to provide continuing challenges for the participants.

6 Principles for Building a Successful Competition Infrastructure

In our opinion the VR Rescue competition has had a completely salutary effect on research in the areas of robotics it affects. This has come about through the network externalities provided by extending a research simulation to the wider audience and support offered by a competition. Additionally, the vigilant guidance of the organizing committee was necessary to focus the competition on research rather than transient issues. It is not clear that other types of competitions will necessarily provide these same benefits.

The issues we feel most relevant for obtaining such an infrastructure benefit are:

Generality The infrastructure benefit accrues because the wedding of robot models to a game engine offered a very general simulation with a wide variety of uses beyond USAR. An examination of our users shows almost half using the simulation for other problems. Simulations restricted to a single problem or setting such as a RoboCup Soccer simulation or a Trading Agents simulation would need to ensure that the domain and adaptations available within the simulation were sufficiently rich to support researchers with different perspectives and problems.

Never build what you can borrow- Earlier simulations, even those incorporating the ODE physics engine, have been forced to develop extensive simulation infrastructures. While accurate robot models are fairly easy, good models of the world incorporating realistic complexity are nearly impossible to build without sophisticated tools. Because both HRI and USAR robotics are focused on robots' interaction with their environment rather than behavior in isolation, fidelity of the world is just as important as fidelity of the robot. By using a game engine, USARSim falls heir to a suite of tools for building and extending realistic environments.

Piggyback the development cycle- Computer graphics and other areas impacted by gameplay have a very rapid development cycle. Taking advantage of these new features as they appear would be impractical for any academically developed simulation. By piggybacking on a game engine whose developers are driven by the market to incorporate new technologies as rapidly as possible, USARSim is able to remain near the state of the art without the expenses associated with development.

Validation is everything- For the communities using USARSim or other simulation with scientific aspirations validation is the most important feature. By offloading the development of the simulator and the need for technology driven revisions, USARSim allows developers the time needed for thorough validation of the platforms and sensors being modeled. It is in fact this emphasis on validation that distinguishes USARSim from most other robotic simulations.

Sustained management- Unlike simulations maintained on an incidental basis by their academic developers, USARSim has benefited from the early involvement and management by NIST personnel. NIST involvement has led to the elimination of ad hoc exceptions and extensions and the codification of extensions in the form of mission packages, the introduction of standard scaling into the simulation, and the ongoing support of in-house and external validation efforts.

The competition, itself, has fostered substantial additional research benefits. Foremost among these has been the introduction of *elemental tests* that allow teams to develop, test, and finally identify best of breed solutions to isolatable problems that contribute to overall team performance. In conjunction with the practice of requiring winning teams to post code for other's use, the results of *elemental tests* provide a clear floor for teams preparing for the next year's competition.

The values of this competition to related research areas has been strongly tied to the guidance of its organizing committee. Not all competitions can be expected to provide similar benefits to research. It is hard to imagine how an equation solving or programming competition, for example, could advance research. Such competitions may serve a motivational function for education but cannot advance knowledge themselves. On other problems there is always the danger of programming to the simulator or solving narrow problems centering around contest rules. It is difficult to prescribe how to solve these problems in the abstract because they are very dependent on the nature of the problem, the technical preparation of the contestants, and the flexibility of the competition. Although it is unsatisfying, the best advice we can give is to pick a good technical organizing committee to get a contest that advances research.

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