

Evolution of Robotic Simulators: Using UE 4 to Enable Real-World Quality Testing of Complex Autonomous Robots in Unstructured Environments

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Abstract: Robotic simulators are essential for control development since they allow early testing. Additionally, trial time is tremendously reduced in comparison to a real system. In the recent past, many powerful simulation systems emerged, offering a high quality and level of realism. Still, those simulators have some shortcomings concerning the development of complex commercial vehicles that regularly operate within extremely cluttered and unstructured environments. This paper aims to reduce the gap occurring during the simulation and real-world testing to increase the expressiveness of robot control software tests.

1 INTRODUCTION

Simulation engines are a powerful tool for the development of robotic systems. They allow early testing, design and sensor optimization, plus improved controller development before tests on the physical platform are performed. However, there exists a gap between testing in simulation and the real world. In the past, complex, relevant features for robot perception could not be completely modeled by the simulator due to the versatility of environments. This is especially true for the development of autonomous commercial vehicles which have specialized supplements and kinematics for task fulfillment. However, the consideration of specialized sensors, sensing disturbances, and the environment is essential for successful control development. With the Unreal Engine 4 (UE 4), a suited framework for photorealistic rendering of complex scenes at the real-time performance is available. In recent literature, many UE 4-based simulators have been proposed. Unfortunately, they do not explicitly address the requirements for complex commercial vehicles and sensing errors in the quality required to reduce the simulation and real-world testing gap.

The following contribution targets the integration

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of the Unreal Engine 4 into the middleware Finroc. Based on the UE 4-Finroc-API, sensors can be modeled in a more realistic way to include necessary characteristics that affect the robot's navigation and perception. Robot control behavior can be tremendously improved through the consideration of such effects. Also, the risk of tailoring a control approach towards (simulation) specific data decreases.

Sect. 2 describes state of the art and evolution of robotic simulators followed by a description of the UE 4-Finroc interface (Sect. 3). Sensors and virtual robot setup is addressed in Sect. 4. Sect. 5 targets specialized actuation. Finally, two applications examples are provided (Sect. 6) and a summary and conclusion follows (Sect. 7).

2 RELATED WORK

Robotic simulators are a common tool for control development. Depending on the application field, there are different requirements for the simulation. According to (Goodin et al., 2018), these can be grouped into three major fields:

Development Environments focus on the basic physical modeling and environment interaction.

Test Environments detailed representation of the environment, more realistic physics and sensor data modeling.

Empirical/semi-empirical simulators application tailored highly realistic physics or sensor data.

Simulation frameworks belonging to the first category are exemplary SimVis3D (Wettach et al., 2010) or Gazebo (Agüero et al., 2015). Both feature a 3D simulation including a physics and render framework as well as a control API. SimVis3D, uses the Newton Dynamics physics engine and Coin3D for visualization while Gazebo relies on the Open Dynamics Engine and initially OpenGL Utility Toolkit (GLUT) but nowadays OGRE. Also, V-REP (Freese et al., 2010) is a multipurpose robot simulator that supports numerous languages and controllers. The user interface enables a simple construction of a robotic system and offers a default sensor suite. Yet, there are limitations when it comes to bigger environments and photo-realistic textures. As an example of second and, to some extent, the third category, Virtual Autonomous Navigation Environment (VANE) (Goodin et al., 2017) can be mentioned. Its focus is on military, off-road unmanned ground vehicles (UGV) and therefore puts strong efforts in material (reflections), weather (sun/rain), dust/haze (atmosphere), and vegetation simulation. Similarly, USARSim (Carpin et al., 2007), an urban search and rescue simulation build on the commercially available Unreal Engine 2.0, is of restricted use.

Unreal Engine 4 (UE4) started to offer photo-realistic rendering, an open-world design, and level of detail processing for free in academic applications in 2014. The prominent CARLA (Dosovitskiy et al., 2017) describes itself as a “simulator for autonomous driving research”. At its core, UE4 does the main physics simulation and rendering work whereas the framework provides a whole lot of tools and resources for testing autonomous car driving in urban scenarios. This includes simulated sensor suites, UE4 content such as vehicles and urban maps as well as support for loading OpenDrive format for map generation. Similarly, AirSim (Shah et al., 2017), Sim4CV (Müller et al., 2017), and Flightgoggles (Guerra et al., 2019) were initially developed for the aim to test computer vision algorithms within the field of drone/UAV applications and are extended for autonomous driving. Pavilion presented by (Jiang and Hao, 2019) focuses on combining UE4 with an interface for ROS using standard ROS messages, yet using no separate bridge application and resolving the binary incompatibility due to Run-Time Type Information (RTTI) and C++-exceptions.

3 SIMULATION FRAMEWORK

Multiple software components are applied to implement and test robotic control systems in simulated

environments. Supplementary to a robot control software framework, a simulation engine allows the modeling of robots and environment to simulate physical properties of those.

3.1 Finroc

The Finroc framework for robot control provides a powerful suite for the development of robot control systems (Reichardt et al., 2013). The central concept is the decomposition of functionality into *modules*. A Finroc program is called *part* while data structures for data exchange are *ports*. They provide an abstraction from the actual communication technology, as TCP. Through information hiding, the communication stack can be easily exchanged. Finroc offers inter-network communication as well as shared memory-based technologies for lock-free and zero-copy data exchange. The Finroc-UE4 simulation uses Finroc data ports for communication.

3.2 Unreal Engine 4

An important criterion for selecting the best-fitted simulation engine is a high performance in visualizing outdoor landscapes and representing vehicles physically correct. Gaming engines are especially suited for this purpose since they perform outstandingly in representing very realistic environments and have feasible realtime simulation capabilities. UE4 offers these features in a powerful way and is therefore selected as simulation. Further, UE4 provides good support for the development of own content and extensions. It provides multiple possibilities for software modules development using an extensive C++ API and BLUEPRINT system. Physical effects use NVIDIA PhysX which allows fast calculations on a GPU. Further, the material and rendering system enables a realistic visualization of the environment.

The overall performance of a robot's sensor is strongly influenced by the sensing quality. Consequently, it is necessary to generate appropriate data to simulate such sensors. Often applied systems are visual sensors like cameras or laser-scanners which especially benefit from simulation realism. UE4 enables data generation that has similar quality to the real-world based on realistic-looking environments.

3.3 Interface Plugin

Finroc and UE4 share data for the transmission of sensor readings and exchange of control commands for simulated actuators. An UE4-Finroc plugin provides an API for both software systems using the C++

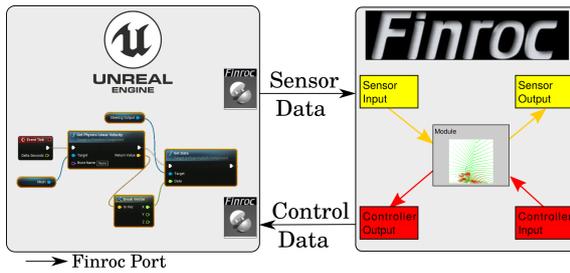


Figure 1: UE4-Finroc interface and data exchange.

programming language. Port functionality of Finroc is loaded by UE 4 due to its modular structure via a shared object file.

The plugin provides specialized UE 4 actor components that wrap Finroc ports (Fig. 1). Those interface components assert data type compatibility and can be attached to any actor. C++ classes and BLUEPRINTS in the UNREAL EDITOR can send or receive data from Finroc ports using the publish and get mechanisms. Continuous data updates can be realized using the actor tick function. Ports transmit data of arbitrary C++ data types. To ensure data compatibility and reduce complexity, a generic UBUFFER type is used for communication together with trivial types as INT, BOOL or FLOAT. Complex data as images use this buffer to transmit a byte stream. The API on Finroc side transforms the actual data to the standard Finroc data type.

Through this communication system, simulation and real hardware abstraction can be easily exchanged. Optimally, no control behavior change can be observed after an abstraction layer exchange.

4 SENSORS

Robot control behavior strongly depends on the equipped sensors and their respective data quality. Therefore, apart from insufficient modeling of kinematics or robot actor’s characteristics, the absence of sensor data characteristics prevents realistic robot control simulations. Thereby, it is not necessarily required that the error is an exact replication of the real-world error but a simulated sensor should have at least the same error characteristic and quality to test the impact on control.

4.1 Localization Systems

Robot localization systems determine the position and orientation within an environment. Localization errors play a critical role in task execution and robot safety.

Inertial Measurement Units. Inertial measurement units (IMU) provide acceleration readings around every translational and rotational axis of a robot. Additionally, the 3D orientation is usually available. IMU data is often prone to integration errors over time. Also, a magnetometer may react to (ferro-)magnetic objects nearby as the vehicle’s frame or (electro-magnetic) motor currents.

The simulated IMU accesses the physic model of the UE 4 robot actor and reads the linear velocity vector \vec{v} as well as the angular accelerations. The velocity is derived using the tick duration Δt to retrieve the linear acceleration $\vec{a} = \vec{v} \cdot \Delta t^{-1}$. Next, the standard gravity is applied to simulate earth gravity. The robot’s rotation can be directly accessed by the IMU actor. Depended on the real IMU model, drifts or slips over time can be added in a preprocessing step to approximate the physical sensor’s quality. This prevents that reintegrated velocities correlate too strictly with the relative velocity of the body to which the IMU is mounted.

Odometry. Odometry data uses the kinematic model of the robot to determine the robot’s motion based on the wheel velocities and steering angle. It is not sufficient to model odometry data by reading the robot’s linear velocity and steering angle directly from the physics since wheel slip is not considered.

Therefore, UE 4 odometry sensors access the skeletal mesh of the robot and read the angular velocities of the corresponding wheel bones. The calculation to determine the robot’s velocity, curvature, and slip angle depends on the kinematic of the robot. The values are determined in the robot specific kinematic model within a preprocessing step.

Global Navigation Satellite Systems. A common global localization sensor is the Global Navigation Satellite System (GNSS). GNSS systems are heavily affected through the environment as shadowing which should be regarded by simulation. The visible satellite constellation is described as the dilution of precision. The horizontal (HDOP), vertical (VDOP), and position (PDOP) dilution of precision calculation depends on the geometric constellation of satellites (Santerre et al., 2017). To save computational power, the DOP computations of the simulated GNSS are approximated from the satellite count only. An exponential regression was used to find constants for the approximation function based on a real-world GNSS data set. The data set was collected using a GatorX855D robot equipped with a Starfire 3000 RTK and an u-blox NEO-7P GNSS receiver. Due to the higher precision, the Starfire served as ground truth. The robot

traveled a closed track at the TUK campus of approximately 500 m. The aim was the determination of effects through occlusions through buildings and the impact on the DOP value.

The approximated values for HDOP, VDOP, and PDOP are computed as follows

$$\text{DOP} = \max\left(\frac{\lfloor a_i \cdot r n_i^{\text{sat}} \cdot 100 + 0.5 \rfloor}{100}, 1.02\right) \quad (1)$$

where sat denotes the number of visible satellites and i stands for the respective DOP. The experimentally determined constants for the exponential regression are depicted in Table 1 and are incorporated by the simulated GNSS receiver.

The GNSS noise affecting latitude and longitude depends further on the visible satellite configuration. The amplitude of the GNSS error ϵ_i is computed as

$$\epsilon_i = a_i \cdot r n_i^{\text{sat}} \quad (2)$$

where $i \in \{\text{HDOP}, \text{VDOP}, \text{PDOP}\}$ corresponds to the previous readings. The amplitude value is multiplied with randomly generated noise generated from the GNSS base precision as stated in the corresponding data sheet. Finally, it is added respectively to the latitude, longitude, and altitude.

The number of visible satellites is split into the general direction of visibility (north, south, east, and west). The GNSS fix category is

$$\text{fix} = \begin{cases} \text{No Fix} & \text{sat} \leq 1 \\ \text{Bad Fix} & 1 < \text{sat} \leq 2 \\ \text{2D Fix} & 2 < \text{sat} \leq 3 \\ \text{3D Fix} & \text{sat} > 3 \end{cases} \quad (3)$$

In the case that at least a single quadrant contains no visible satellites, the 3D Fix degrades to a 2D Fix. It follows, PDOP = 0 for 2D fixes. Additionally, DOP values are not available for No Fix or Bad Fix.

The GNSS simulation realization uses raytracing to determine the visibility of the receiver. Hereby, a satellite manager spawns satellites which are located and distributed above the scene. Each simulated GNSS receiver accesses the satellite manager to get a reference on the available satellites. Each receiver performs a ray trace on each satellite to determine visibility. A coding example is given in Alg. 1.

Table 1: Experimentally derived constants of the DOP approximation though exponential regression.

Constant	Value	Constant	Value
a_{HDOP}	5.59474	r_{HDOP}	0.854736
a_{VDOP}	10.2524	r_{VDOP}	0.858869
a_{PDOP}	2.63625	r_{PDOP}	0.967947

Algorithm 1: Code snippet to determine satellite visibility with UE 4 GNSS receiver.

```

1 FHitResult hitresult (ForceInit);
2 FCollisionQueryParams ft_par =
   FCollisionQueryParams (FName(TEXT("FireTrace")),
   true, this);
3 ft_par.bTraceComplex = true;
4 bool hit = GetWorld()->LineTraceSingleByChannel(
   hitresult, satellites[i]->GetActorLocation(),
   this->GetActorLocation(), ECC_Pawn, ft_par);

```

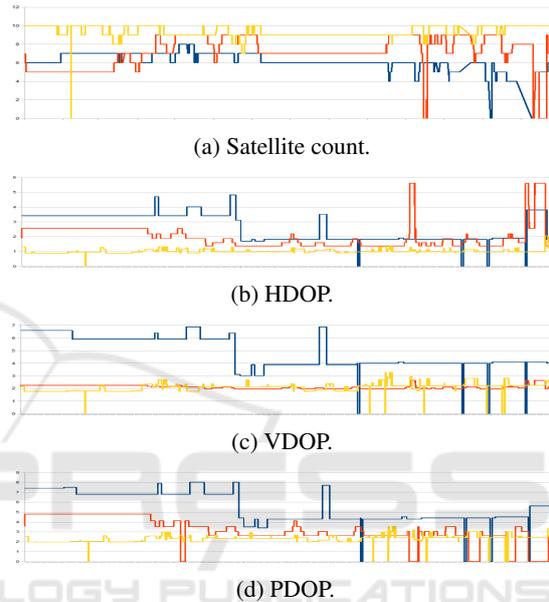


Figure 2: Real-World data plotted against the traveled distance (blue: Starfire 3000 RTK, yellow: u-blox NEO-7P) with comparison to the reenacted simulation trial on the virtual TUK campus (red: simulated GNSS).

For validation purposes, the simulated GNSS has been compared to the real world GNSS signals. Therefore, a simulated data set was recorded on the UE4-TUK campus by replicating the initial drive. The simulated number of GNSS satellites and DOP values are plotted against the robot position as depicted in Fig. 2. It can be observed that the satellite count of both real-world GNSS systems (blue Starfire 3000 RTK, yellow u-blox NEO-7P) differ from each other even if there are at a similar location on top of the robot. However, the simulated signal (red) has a similar quality as the real systems. This is also visible for the DOP results where the simulation signal resembles the u-blox receiver.

4.2 Vision-based Sensors

It can be distinguished between different classes of vision sensors like cameras, depth cameras, or laser

scanners. Effects on the vision system as exposure, or dust can be easily modeled using post-processing and particle systems.

Generic Cameras. Simulated cameras utilize the UE 4 render pipeline. Cameras properties as field of view or resolution are defined in the respective camera component and the corresponding render target of the engine according to the sensors data sheet. The simulated camera enqueues a non-blocking render command and publishes the data when the rendering process is finished. Therefore, it is possible to use a large set of cameras in complex scenes without slowing the tick system. Specialized cameras can be easily implemented by inheriting the base class and adapting the respective properties and post-processing materials. The properties of the camera can be adapted through the control software, for instance, updates can be triggered by the perception system of the robot.

Stereo and Depth Cameras. Stereo or depth cameras provide distance information in addition to color data. A common approach to simulate distance sensors is reading the depth buffer of the simulation render engine. However, stereo cameras rely on the matching of a calibrated image pair. The matching process introduces a backward distortion of the point cloud resulting from the image disparity. Reflections, insufficient texture, and disturbances of the device's lenses typically cause spurious obstacles or gaps within point data. Moreover, uncertain obstacle boundaries are common.

A more lifelike sensor version, but also computationally more expensive, uses semi-global matching of two rendered images (Hirschmüller, 2008) as depicted in Fig. 3. Accordingly, two generic camera actors with parallel arranged lenses start a simultaneous rendering of the scene. The resulting image pair has to be rectified and matched.

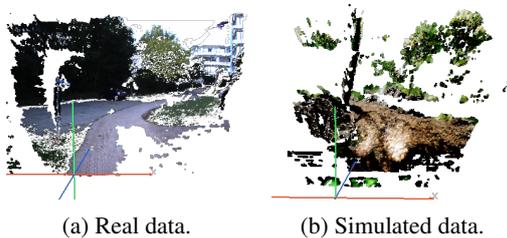


Figure 3: Real and unreal stereo colored point cloud data with characteristic stereo matching disturbances.

360-Degree Cameras and Laser Scanners. A 360-degree camera can be realized using multiple generic camera actors. An orientation change is ap-

Algorithm 2: Pseudo code for hyperbolic distortion of pixel mapping.

```

Data: render resolution, laser resolution, beam angles
Result: index mapping
1 determine pixels per beam;
2 determine zero angle pixel;
3 for  $y \in$  vertical laser resolution do
4     determine distance to zero pixel;
5     for  $x \in$  horizontal laser resolution do
6         hyperbola = calculate hyperbola (
7             asymptote  $a \rightarrow$  distance to zero pixel
8             asymptote  $b \rightarrow$  horizontal render resolution / 2
9             value  $\rightarrow -$  horizontal render resolution / 2 +  $x$ );
10        if distance to zero pixel negative then
11            hyperbola = -hyperbola;
12        re-apply zero angle pixel offset to hyperbola;
13        limit hyperbola to pixel bounds;
14        index mapping( $x,y$ ) = ( $x$ , hyperbola);
    
```

plied to scan a full cylinder or respectively sphere. Based on the UE 4 camera's maximum FOV of 170° , three cameras are required to record a 360-degree image.

In contrast to stereo cameras, lidar sensors can be implemented using depth rendering. Since the lidar's precision, and range is higher than these of a stereo camera no additional introduction of distortions is required. Simulated particle effects as dust affect the engine's depth buffer which corresponds to a real sensor behavior that reacts strongly to environmental particles and provides spurious readings.

Often, the vertical opening angle is smaller than the horizontal angle since the laser count is often rather small (e.g. 16 – 128 lines). A lower vertical resolution has to be regarded by skipping lines of the depth image which has typically a higher resolution due to quadratically rendered pixels. Skipping lines under the consideration of the horizontal offset generates a linear rendered image (Fig. 4a). This rendering is feasible for some lasers as single-line lasers. In the case of a rotating laser scanner, a hyperbolic distortion can be observed in the point cloud due to the polar coordinate mapping of the rotating beam. This distortion can be approximated using a hyperbolic point mapping in the dense depth image (Fig. 4b). The hy-

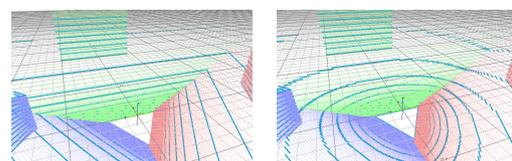


Figure 4: 360 degree depth camera using three render targets (red, green, purple blue). Laser data with a lower vertical resolution can be approximated (blue). The laser's rotation is approximated using hyperbolic distortions.

parabolic equation is given with

$$h = \sqrt{a^2 + \frac{x^2 \cdot a^2}{b^2}}. \quad (4)$$

The resulting pixel mapping is explained in Alg. 2.

The simulated point cloud approximates well to real point cloud data as it can be seen on the example of a simulated Velodyne HDL-32E laser scanner using 32 laser lines (Fig. 5). However, it can be observed that the data close to the scanner built a triangle-shaped point pattern based on the rendering using multiple camera frustums. This effect can be avoided if needed using ray-based techniques or through vertical oversampling of the depth images.

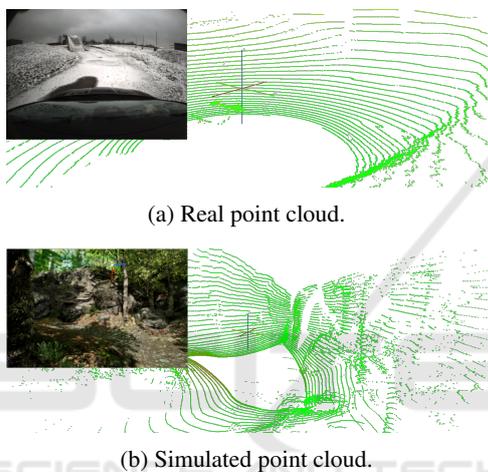
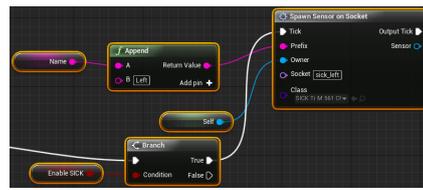


Figure 5: Real and simulated Velodyne HDL-32E point clouds. The scanner has 32 scan lines with a vertical field of view of 41.33° and vertical offset of -20°.

4.3 Robot Setup

The UE4 editor is used for robot setup and sensor placement. Therefore, sensor sockets are added to the robot's skeletal mesh. This allows a constructive approach based on the mesh and therefore real sizes and shape of the robot. Accordingly, optimum sensor positions can be determined and the corresponding best mounting position on the robot tested. Depending on the mesh quality, unconsidered effects as obstructions through parts of the vehicle, blind spots, or small building spaces can be early detected.

The robot spawns the sensor within the main blueprint at the begin of play. Therefore, it uses a macro blueprint for spawning and attaching the sensor actor to the desired sensor socket (Fig. 6a). The socket can be adapted in the robot's skeleton and the physical robot may use the layout which performed best in the preliminary tests (Fig. 6b).



(a) Spawn sensor on socket.



(b) Skeleton and virtual sensor on socket.

Figure 6: Virtual sensor placement to determine the best mounting position.

5 ACTUATORS

Besides the recognition of the environment, autonomous systems interact through controlling the motion or actuators of associated vehicles. Hereby, degrees of freedom should be similar to the real machine. Some vehicles, particularly commercial or specialized vehicles, used some unique configurations.

5.1 Driving Kinematics

Commercial vehicles often consist of special driving kinematics which cannot be realized by a standard Ackermann steering. Therefore, the use of the wheeled vehicle template class in UE4 is strictly limited. Exemplary, an Unimog U5023 special truck has an axle shrinking of 30° front axis, and 15° rear axis, portal axles for higher ground clearance, differential locks, 14 gears, and a tire inflation system to adapt friction during navigation (Fig. 7a). For simulation, additional joints were built into the skeleton of the vehicle to model the additional properties. The axle can rotate using a joint and two springs for stabilization. The adaptable tire friction is simulated by changing the tire's friction parameters during runtime. Gears and differential setup is used from the UE4 vehicle



(a) Axle shrinking. (b) Pivot steering.

Figure 7: Ackermann-based special driving kinematics.

base class and parameterized according to the U5023 data sheet and adapted during runtime through Finroc ports.

In contrast, the autonomous tandem roller BW 174 is controlled by a pivot-steering (Fig. 7b). Therefore, a custom double Ackermann steering class was created by implementing the bicycle kinematics. It accesses the steering joints and controls the respective angular velocities. Supplements as edge cutters or chip spreaders are controlled through the skeleton of the vehicle.

5.2 Complex Body Actuation

To test control software for excavation applications, a simulation model of an excavator requires to have similar characteristics as the real machine. It is not necessary to rebuild the excavator dynamics completely realistic, but it has to fit the used control algorithms.

Parallel Kinematic Chains. An excavator arm has a very characteristic kinematic. It consists of segments that are moved with hydraulic cylinders. This hydraulic system is connected to the moving segment in an own kinematic chain which is placed in parallel to the actual segment (Groll et al., 2015). The excavator arm is modeled as a bone structure of the physical enabled skeleton mesh. It is organized as a tree structure and single parts can be connected by moveable joints. For each part of the excavator arms kinematic structure, a bone is created. Each bone has a body that is used as a representation for the weight including the weight distribution to allow a physical solid-body simulation. All of the main elements of the excavator arms are connected with a revolute joint to the previous one. A parallel kinematic chain is added to each of the main parts which include the hydraulic drives to move the appropriate body part. In all of these chains, the hydraulic cylinder is modeled as a prismatic joint with an enabled drive. Fig. 8 provides an overview to the crowd kinematics.

It starts with the boom body at which the main crowd's body is connected with a revolute joint. To

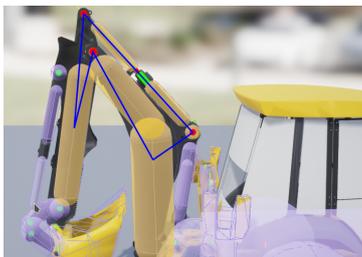


Figure 8: Configuration of the hydraulic actuator.



(a) Autonomous off-road navigation.



(b) Autonomous excavation.

Figure 9: Applications of commercial vehicle robots.

this body the piston rod is linked by another rotational joint. Following by the base of the cylinder which is connected by the driven prismatic joint. The last part of the chain is built by a spherical body which is used to connect the hydraulic chain back to the boom.

Hydraulic Actuators. Hydraulic cylinders produce a movement that has a velocity proportional to the flow rate of the hydraulic oil generated by the pump system. This can be influenced by the opening of a valve which is normally controlled by commands given from the joysticks. In the autonomous control system these joystick commands are generated by the control software. A spring-damper system is used for generating the forces which are used by the drives to move the connected bodies. It uses the velocity error as well as the position error to calculate the force:

$$\text{force} = \text{spring} * (\text{targetPosition} - \text{position}) + \text{damping} * (\text{targetVelocity} - \text{velocity}) \quad (5)$$

Besides the target velocity, a target position as control input for the drive is needed as well. To deliver this value a control system is added to the hydraulic drive which calculates the actual expected position depending on linear velocities and the time which has passed.

6 APPLICATION & SCENARIOS

The presented simulation framework is used in various scenarios and applications. In the following, two examples are provided which benefit strongly from the simulation.

The first example is the autonomous Unimog U5023 (Fig. 9a). The focus of this robot is safe and reliable off-road driving inside cluttered environments. UE 4 provides very realistic environments that

help to identify the relevant features for off-road navigation. The control system of the vehicle could be evaluated using the same simulated sensor set as the real systems. Safety-critical navigation and inclination tests can be performed which is not possible for the real system. The other scenario shows an excavator in an open-pit mine (Fig. 9b). The evaluation of rock recognition was done in simulation and the results transferred to the real machine. Periodical tests with the real machine show that the developed methods are easily transferable to the real world.

7 CONCLUSION

The paper presented a simulation framework tailored to autonomous commercial vehicles operating in cluttered off-road environments. For this purpose, it integrated the Unreal Engine 4 and the robot control framework Finroc. Short-comings of current simulation systems have been identified, starting with a review of the state of the art in robot simulation. Next, the integration of frameworks and communication were explained. Different sensors, special driving kinematics, and complex body actuation were described and an application overview provided. It could be observed that the simulation and real-world testing gap could be significantly reduced.

Future and current work aims to integrate more sensor systems, e.g. radar, and disturbances, like realistic ferro-magnetic behavior of vehicle frames. Further, automated testing should be regarded that allows a statistical evaluation of the control behavior and allows unit testing of control functionality.

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REFERENCES

- Aguero, C., Koenig, N., Chen, I., Boyer, H., Peters, S., Hsu, J., Gerkey, B., Paepcke, S., Rivero, J., Manzo, J., Krotkov, E., and Pratt, G. (2015). Inside the virtual robotics challenge: Simulating real-time robotic disaster response. *Automation Science and Engineering, IEEE Transactions on*, 12(2):494–506.
- Carpin, S., Lewis, M., Wang, J., Balakirsky, S., and Scrapper, C. (2007). Usarsim: a robot simulator for research and education. In *Robotics and Automation, 2007 IEEE International Conference on*, pages 1400 – 1405. IEEE.
- Dosovitskiy, A., Ros, G., Codevilla, F., Lopez, A., and Koltun, V. (2017). Carla: An open urban driving simulator. In *1st Conference on Robot Learning (CoRL 2017)*, pages 1–16, Mountain View, United States.
- Freese, M., Singh, S., Ozaki, F., and Matsuhira, N. (2010). Virtual robot experimentation platform v-rep: A versatile 3d robot simulator. In N. Ando et. al., editor, *International Conference on Simulation, Modeling and Programming for Autonomous Robots (SIMPAR)*, volume 6472 of *Lecture Notes in Computer Science*, pages 51–62. Springer.
- Goodin, C., Carrillo, J. T., McInnis, D. P., Cummins, C. L., Durst, P. J., Gates, B. Q., and Newell, B. S. (2017). Unmanned ground vehicle simulation with the virtual autonomous navigation environment. In *2017 International Conference on Military Technologies (ICMT)*, pages 160–165.
- Goodin, C., Doude, M., Hudson, C., and Carruth, D. (2018). Enabling off-road autonomous navigation-simulation of lidar in dense vegetation. *Electronics*, 7:154.
- Groll, T., Hemer, S., and Berns, K. (2015). Autonomous backhoe loader. In *6. Fachtagung Baumaschinentechnik 2015: Maschinen, Prozesse, Vernetzung*, volume 49 of *Schriftenreihe der Forschungsvereinigung Bau- und Baustoffmaschinen e.V.*, pages 351–366.
- Guerra, W., Tal, E., Murali, V., Ryou, G., and Karaman, S. (2019). Flightgoggles: Photorealistic sensor simulation for perception-driven robotics using photogrammetry and virtual reality. *CoRR*, abs/1905.11377.
- Hirschmüller, H. (2008). Stereo processing by semiglobal matching and mutual information. *IEEE Transactions on pattern analysis and machine intelligence*, 30(2):328–341.
- Jiang, F. and Hao, Q. (2019). Pavilion: Bridging photorealism and robotics. In *2019 International Conference on Robotics and Automation (ICRA)*, pages 8285–8290.
- Müller, M., Casser, V., Lahoud, J., Smith, N., and Ghanem, B. (2017). Sim4cv: A photo-realistic simulator for computer vision applications. *International Journal of Computer Vision*.
- Reichardt, M., Föhst, T., and Berns, K. (2013). On software quality-motivated design of a real-time framework for complex robot control systems. In *Proceedings of the 7th International Workshop on Software Quality and Maintainability (SQM), in conjunction with the 17th European Conference on Software Maintenance and Reengineering (CSMR)*, Genoa, Italy.
- Santerre, R., Geiger, A., and Banville, S. (2017). Geometry of gps dilution of precision: Revisited. *GPS Solut.*, 21(4):1747–1763.
- Shah, S., Dey, D., Lovett, C., and Kapoor, A. (2017). Airsim: High-fidelity visual and physical simulation for autonomous vehicles. In *Field and Service Robotics*, pages 621–635. Springer.
- Wettach, J., Schmidt, D., and Berns, K. (2010). Simulating vehicle kinematics with simvis3d and newton. In *Proceedings of the 2nd International Conference on Simulation, Modeling, and Programming for Autonomous Robots (SIMPAR'10)*, pages 156–167, Darmstadt, Germany. Springer-Verlag Berlin.