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Sampled-Data Control Approach for Unmanned Ground Vehicles Using RTK Sensors

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Abstract

In this paper, we study simulation and experimental verification of a sampled data control approach for an unmanned ground vehicle (UGV). Our research vehicle is a differential wheeled robot with an RTK sensor, lidar and camera, however in this work only the RTK sensor is used. The rationale for adopting a sampled-data control approach is as follows: RTK sensor output is usually a 1 Hz signal, but the position and orientation control loop of the UGV usually runs at much higher frequencies. We study the trajectory following problem and propose a sampled-data control approach to minimize the tracking error. Both simulation and experimental results that are presented in this work demonstrate the effectiveness of the proposed approach.

Keywords:
Unmanned Ground Vehicles (UGV), RTK, Autonomous Navigation, Robust Control.

1. Introduction
In this paper, we study simulation and experimental verification of a sampled data control approach for an unmanned ground vehicle (UGV), see Figure 1. UGV's have been extensively studied in the literature [1]–[8], and the robot operating system (ROS) is widely used as the main system software. Our research vehicle is a differential wheeled robot and is not based on ROS. Instead, a simpler lightweight software stack is used to minimize delays and improve the responsiveness. The UGV shown in Fig. 1 has an RTK sensor, lidar and camera, however in this work only the RTK sensor is used. The rationale for adopting a sampled-data control approach is as follows: RTK sensor output is usually a 1 Hz signal, but the position and orientation control loop of the UGV usually runs at much higher frequencies. In this work, we focus on the autonomous path following problem and propose a sampled-data control approach to minimize the tracking error. Our initial experimental results demonstrate the effectiveness of the proposed approach.

This paper is organized as follows. In Section II, we present the UGV architecture, and summarize electrical, firmware and software details. In Section III, we present the UGV system model, and In Section IV, we present the details of the proposed sampled-data control algorithm. In Sections V and VI, we present simulation and experimental results respectively. Finally, concluding remarks and future research directions will be presented at the end.

2. Electrical, Firmware and Software Details
The unmanned ground vehicle used in this study is a research testbed developed by the authors for rapid prototyping of autonomous robotics ideas, see Figure 1. In Toker and Adla (2025), authors studied a pure lidar based trajectory following problem and presented both simulation and experimental results for the same UGV shown in Figure 1. Once again, this work is based on using only the RTK sensor and follows a sampled-data control paradigm.

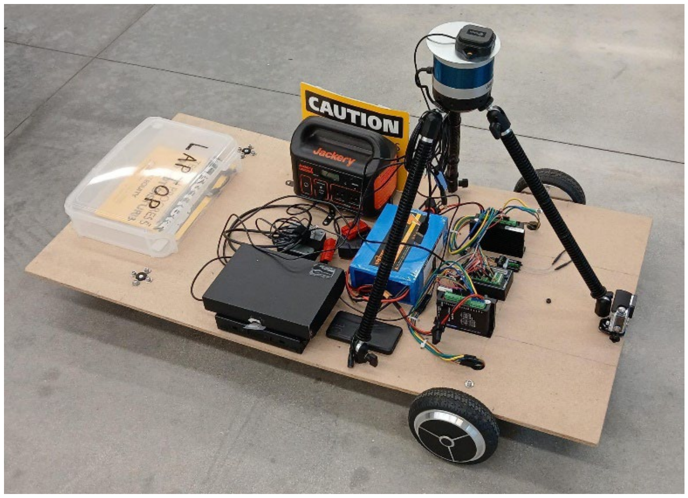

Figure 1. The UGV developed by the authors. In this work, only the RTK position sensor is used.

The UGV has two generic hoverboard motors and two caster wheels. There are also two BLD- 510B brushless DC (BLDC) motor drivers, see StepperOnline (2025), a generic 36V Li-Ion battery, a power station, and an ATmega328P microcontroller placed inside a metal enclosure with screw terminals. Embedded system firmware communicates with the brushless DC motor drivers using the standard 5V TTL PWM signals from the microcontroller. In the event of an emergency, there is also a backup remote control subsystem for manual override.

3. The UGV Vehicle Model

If x, y are the position of the robot, and ϕ is the heading with respect to the x-axis measured in counterclockwise direction in radians, the UGV vehicle model will be

$$\frac{d}{dt}\begin{bmatrix} x \\ y \\ \phi \end{bmatrix} = \begin{bmatrix} \cos(\phi) & 0 \\ \sin(\phi) & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} (v_R + v_L)/2 \\ (v_R - v_L)/b \end{bmatrix}$$

where *(x, y)* is position, ϕ is orientation, v_R and v_L are the right and left wheel speeds, and *b* is the distance between two wheels.

4. Robust Sampled-Data Control Approach

In this section, we define the robust sampled-data control problem for our UGV and propose a Monte- Carlo approach type solution procedure. The UGV's state space is R^3. If at a particular sampling (RTK sampling) time, position and orientation coordinates are measured as $X_t = (x_t, y_t, \phi_t)$, then the actual position and orientation of the UGV will be in the neighborhood (A three-dimensional cube) defined by

$$N(X_t) = (x_t + E_x) \times (y_t + E_y) \times (\phi_t + E_\phi)$$

where E_x, E_y, E_ϕ are internals around the origin, and $\times$ is the cartesian product symbol. At any given time, the set of all possible control inputs, $(w_R, w_L) \in R^2$ will be a one- dimensional set, because we impose a constant speed constraint, i.e. $(w_R + w_L)/2 = w_o$ where w_o is a constant throughout the whole experiment. This control input space is denoted by *C*.

The robust sampled data control problem is defined as the min-max problem

$$\min_{(w_R, w_L) \in C} \max_{X \in N(X_t)} \{\|Y_{t+1} - Y\| \ : \ X \to_{(w_R, w_L)} Y\}$$

where $X \to_{(w_R, w_L)} Y$ means if the UGV state is X at time t, and the control input is (w_R, w_L) between $[t, t+1)$, the UGV will reach to the state Y at time $t + 1$. The state vector Y_{t+1} is the state that we would like to achieve/approach at time $t + 1$, and will be updated according to a well-defined policy after each iteration (Similar to a pure pursuit type approach). If we define

$$U(X, Y_{t+1}, w_R, w_L) = \{\|Y_{t+1} - Y\| \ : \ X \to_{(w_R, w_L)} Y\}$$

then the robust sampled data control algorithm can be defined as follows:

Algorithm 1 Robust Sampled Data Control Algorithm

while `True` **do**

Get the RTK position and orientation data X_t

Pick the next target state vector as Y_{t+1}

Solve the min-max problem

$$\arg \min_{(w_R, w_L) \in C} \max_{X \in N(X_t)} U(X, Y_{t+1}, w_R, w_L)$$

Apply the control input (w_R, w_L) between t and $t + 1$.

end while

The min-max problem in Algorithm 1 can be solved by using randomized sampling of the control input space. Because of the constant speed requirement and the physical limits on right and left wheel speeds, the control input space is 1-dimensional and finite. Therefore, both brute-force search and randomized sampling can be used to solve the min-max problem presented in Algorithm 1.

5. Simulation Results

In this section, we present simulation results for a differential wheeled robot with b = 0.75m The desired trajectory for this simulation study is selected as

$$x(\alpha) = 3(1 + 0.3\cos(0.01\ \alpha))\cos(0.02\ \alpha)$$
$$y(\alpha) = 2(1 + 0.2\cos(0.01\ \alpha))\sin(0.01\ \alpha)$$

where $\alpha \in R$. This equation defines a closed path, and the initial point is not on the trajectory. As it can be seen in Figure 2, the control algorithm needs some time for convergence and after that follows this complex egg-shaped path with relatively good tracking performance.

6. Experimental Results

In this section, we present our experimental results. Our desired trajectory is shown in Fig. 3, and the full video of the experiment is shown in Fig. 4. Experimental tracking performance results are shown in Fig. 5. The sampled-data controller used in this study achieved average tracking error of 25 cm. The histogram of the tracking error is shown in Figure 6.

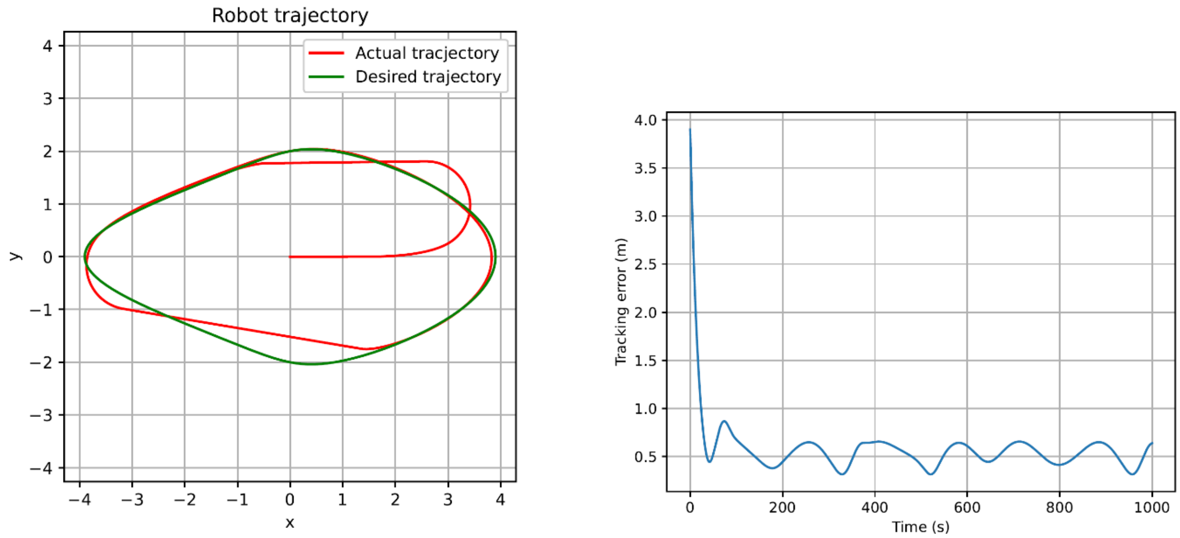

Figure 2. Simulation results for the proposed control algorithm.

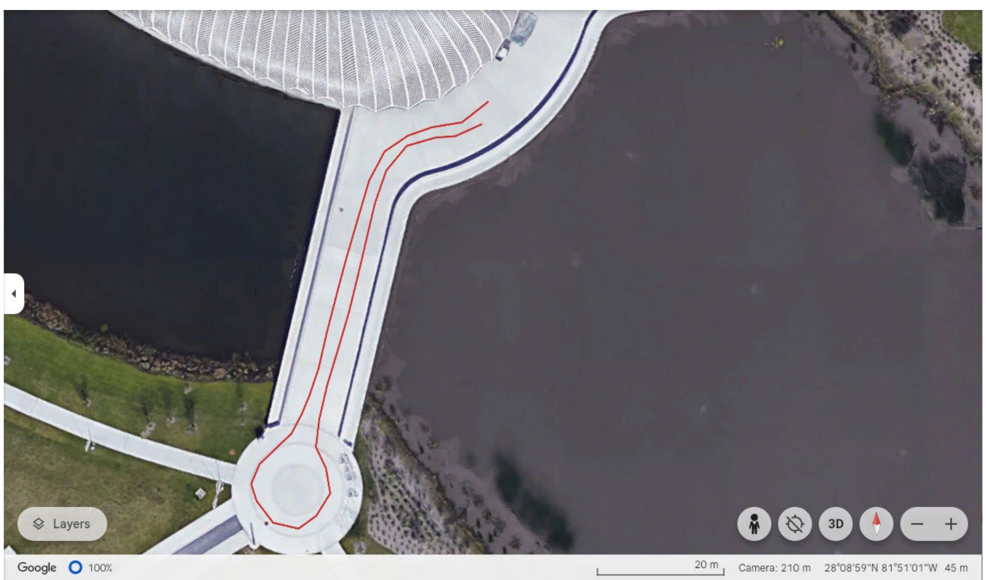

Figure 3. Google Earth view of the desired trajectory.

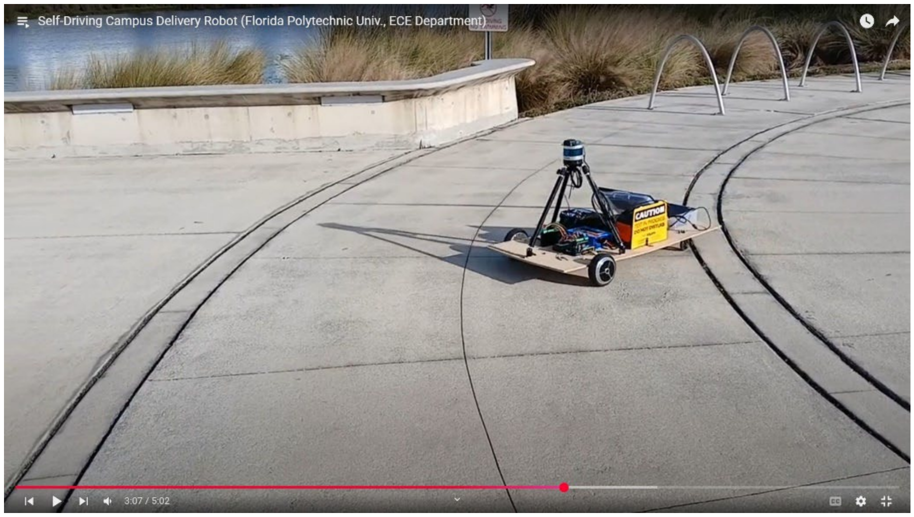

Figure 4. Full video of the experiment is available at https://youtu.be/re05JsABOHE

7. Conclusion

Our initial experimental results that are presented in this work demonstrate the effectiveness of the proposed approach. Both simulation and experimental results validate the developed techniques. Pure RTK sensor based UGVs are suitable for cost sensitive applications, but in the future authors are planning to explore limited sensor fusion-based techniques to improve the tracking performance.

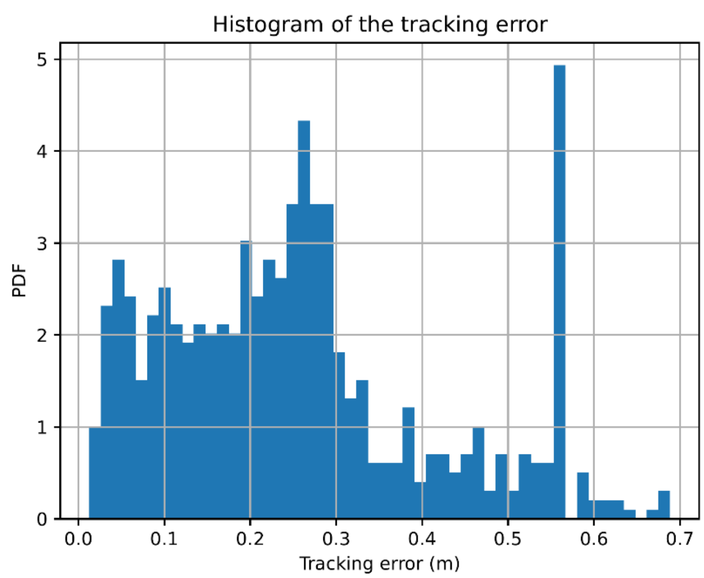

Figure 5. Histogram of the tracking error.
The horizontal axis is tracking error in meters, and the vertical axis is the PDF.

Acknowledgements

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