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Implementation of a predictive shift strategy through radar-based uphill gradient recognition in tractors

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This paper explains how predictive adaptation of an existing shift strategy can be implemented within the transmission control of agricultural machinery. An active sensor on the vehicle is used to accomplish this adjustment. A radar sensor from the automotive environment is attached to the vehicle, and appropriate algorithms for recognizing uphill gradient are implemented using raw radar data. The processing unit sends the results of the uphill gradient determination to transmission control, allowing the transmission ratio to be adjusted in advance to the terrain ahead. In this way it is guaranteed that the optimum transmission ratio is set for the respective uphill gradient even before the vehicle begins to ascend.

Keywords
Intelligent shift strategy, intelligent transmission ratio selection, uphill gradient recognition, radar sensor

Today, the shift strategy for off-highway machinery (with agricultural machinery used as an example here) is determined using rule-based algorithms. These allow transmission control to set the correct gear or the correct transmission ratio (powershift or continuously variable transmission) as well as the corresponding input speed according to the internal transmission signals. Through adjustment of the various parameters of the shift strategy, the performance or fuel consumption is adjusted according to what is required. Within a certain range, this can usually be influenced by operator inputs, giving the driver the option of focusing on performance or on reducing the vehicle's fuel consumption. The shift strategy using rule-based algorithms responds to the current conditions of the environment based on transmission-internal signals as well as external signals available around the vehicle (engine speed, engine load, output speed, etc.). The shift strategy responds to rapidly changing environmental conditions – in this case uphill gradients – with a delay.

To prevent the vehicle from decelerating in case of unpredictable driving events (such as an uphill gradient) until the vehicle comes to a stop, an active environmental sensor (such as radar) allows the vehicle to recognize what is going on in its environment. The radar is mounted at the vehicle's highest point in order to guarantee that the sensor has the best-possible view of the surroundings. The raw data it generates is evaluated by a high-performance computer (HPC) (ZF Friedrichshafen AG n. d., c). In this case, a high-performance computer is understood as a processing unit that has additional memory and greater computing power than what you would usually find in a transmission control unit. This HPC also has interfaces (such as automotive ethernet) for direct connection of a sensor, along with a CAN interface for communication with the transmission control unit. An operating system runs on the HPC, and this operating system in turn enables the use of the Robot Operating System (ROS). The vehicle provides additional information to the HPC. This is necessary to estimate

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the vehicle's position. The algorithms determine the distance between the vehicle and the uphill gradient as well as its angle. Once this data has been determined, the vehicle communication bus makes it available to the transmission control unit. On the basis of this information, it is then possible to intelligently and predictively adjust the shift strategy before the vehicle drives onto the uphill gradient. The optimum transmission ratio is then always set appropriately for the terrain ahead. On test drives of the system, the uphill gradient was correctly recognized, and the corresponding response from transmission control to the uphill gradient was implemented in the vehicle. The predictive shift strategy presented here can be used everywhere and transferred to other mobile off-highway machinery.

State of the art

Cars and commercial vehicles can respond to the topography in front of them using GPS and existing maps. Appropriate algorithms can then adapt the respective shift strategy to the current environmental conditions, thus helping to save fuel and to operate the vehicle more efficiently (ZF Friedrichshafen AG n. d., b).

In off-highway environments, maps are rarely available, or the terrain changes over time, such as on a construction site. This means that the solution of using a GPS signal linked to an existing map is out of the question. To overcome this limitation, an active sensor is used to recognize the current environment.

Description of the system structure

During research into this question, various hardware items and algorithms were investigated in order to find an appropriate solution for intelligent adaptation of the shift strategy to changing environmental conditions. Implementing the system involved extension of the agricultural machinery (from volume production) to integrate prototypical hardware that could use radar to recognize uphill gradients in front of the vehicle. For this, the radar in use was rotated by 90° for installation (Figure 1).

Figure 1: Radar mounted on agricultural machinery (© ZF Friedrichshafen AG)

We will explain the reason for this deviation during installation in the following. The radar transmits the signals to a high-performance computer as shown in Figure 2. This HPC runs a specially developed algorithm that recognizes uphill gradients in front of the vehicle. A ROS framework was used to evaluate the raw radar data.

Figure 2: Installation of the system in agricultural machinery: HPC with display showing uphill gradient recognition (© ZF Friedrichshafen AG)

The functional architecture as described in Figure 3 allows the use of the algorithms developed in existing vehicle control units as long as these are provided with the necessary interfaces to the sensors and transmission control as well as resources (memory, runtime) sufficient for allowing the algorithms to be implemented. The two blocks with the algorithms can also be executed in a single control unit.

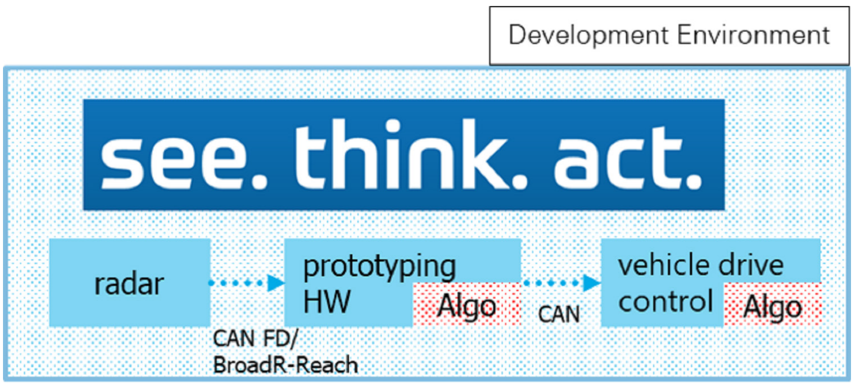

Figure 3: Embedding the algorithms in the development environment (© ZF Friedrichshafen AG)

Radar-based uphill gradient recognition – functional description

During implementation, a radar sensor was selected to enable environment recognition. To allow the environmental sensor to optimally fulfill its task, it was necessary to first determine a position that restricts the sensor's field of view as little as possible. As the field of view of the sensor can be impaired by attached equipment, the sensor was mounted above the windshield of the driver's cabin of the agricultural machinery. The arrangement is shown in Figure 4.

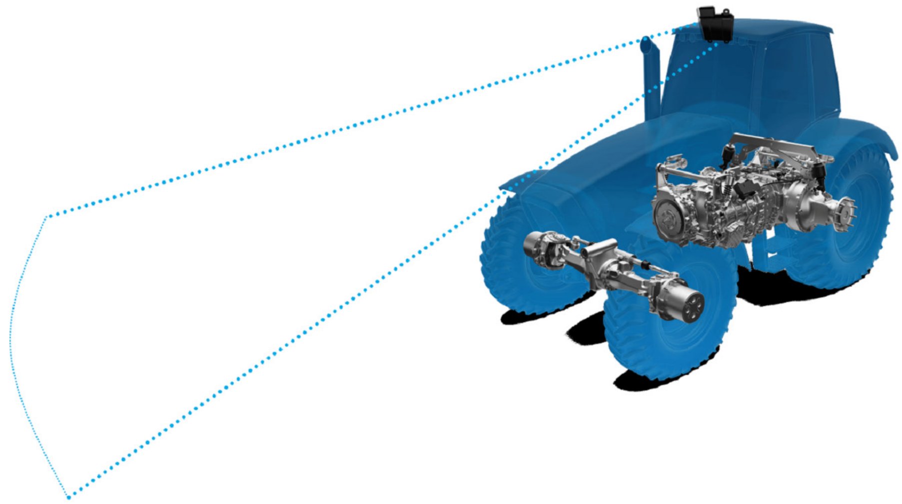

Figure 4: Assembly of radar on agricultural machinery (schematic view) (© ZF Friedrichshafen AG)

How a radar sensor works is briefly explained here. The radar sensor emits electromagnetic waves, which are reflected by target bodies. These reflected waves are then received back by the radar. Radar waves are directional waves that are emitted and detected using antennas. The distance of the target body to the radar can be found by determining the "time of flight," and its position can be deduced based on the angle of arrival. At the same time, the Doppler effect can also be used to detect the speed of each radar point (Fraunhofer IAF 2020, Spektrum Akademischer Verlag 1998)

The radar sensor has a resolution that differs in azimuth (horizontal) and elevation (vertical), as shown schematically in Figure 5. That is why the mounting direction is crucial in this case.

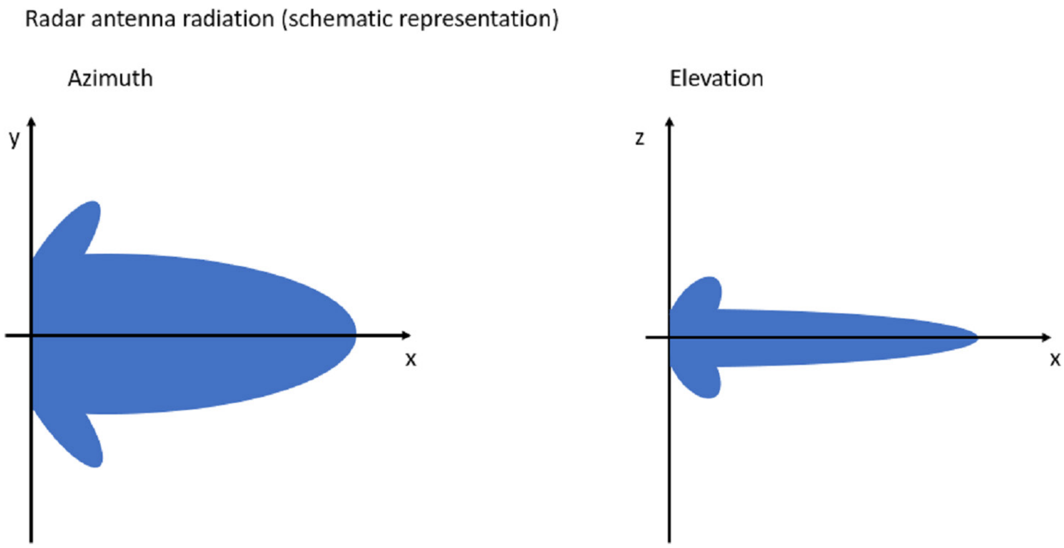

Figure 5: Radar cone (schematic representation) (© ZF Friedrichshafen AG)

In order to achieve better vertical resolution for uphill gradient recognition, the unit is rotated by 90° compared to its use in the automotive environment, as previously mentioned. In the automotive environment, such as on highways, horizontal environmental information is usually being sought. However, in the off-highway example here, the interest lies in environmental information in the vertical direction. With the new installation position, it is possible to make better use of the larger field of view of the azimuth sensor. If only the elevation resolution were evaluated, the field of view would be very limited, and the very few reflected targets would make it nearly impossible to recognize uphill gradients. For the prototypical implementation of uphill gradient recognition, an HPC was used for calculation of the algorithms. All uphill gradient recognition algorithms are based on the raw data from the radar sensor, which is transmitted to the processing unit using the BroadR-Reach interface. The processing unit calculates the uphill gradient ahead of the agricultural machinery and sends the detected values (distance to and angle of the uphill gradient) to the transmission control unit via the vehicle CAN. The transmission control unit sends the vehicle speed and the steering angle to the algorithm in the HPC. This information is required for estimating the movement of the vehicle.

The process of the function is as follows. The agricultural machinery is driving towards an uphill gradient as shown in Figure 6 (ZF Friedrichshafen AG n. d., a).

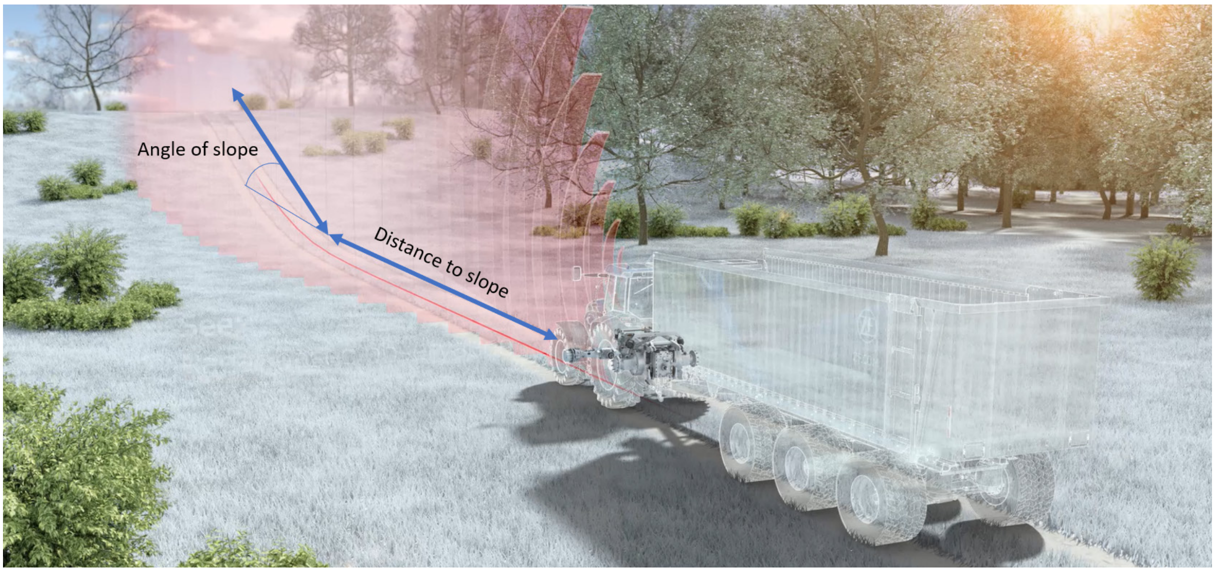

Figure 6: Illustration of agricultural machinery, radar scan and environment (© ZF Friedrichshafen AG)

The radar sensor continuously scans the road ahead of the vehicle. The calculated data of the HPC is cyclically sent to the transmission control unit via CAN. The transmission control unit makes appropriate adjustments to the shift strategy in due time before an uphill gradient. With a continuously variable transmission, for example, this uphill gradient recognition causes the engine speed to be increased and the transmission ratio to be adapted accordingly, at an adjustable distance to the uphill gradient, in order to increase the power reserve of the engine. For powershift transmissions, the shift strategy avoids an unfavorable upshift before the uphill gradient. This prevents downshifting on the uphill gradient and allows the agricultural machinery to climb the uphill gradient faster. Depending on the driving condition, a downshift can also be initiated in good time. Looking ahead using the environmental sensor system enables the drive to respond intelligently and in due time to changes in the environment.

SEE – THINK – ACT

The agricultural machinery uses the radar sensor described above to recognize an uphill gradient (SEE). The data determined by radar is transmitted in raw format. To recognize an uphill gradient, the data received must first be reassembled into the correct order. This requires an occupancy grid, which displays the acquired data with the correct distance from the radar sensor and at the corresponding vertical height.

In the THINK part of the chain, the individual algorithms necessary for recognizing an uphill gradient are applied. Figure 7 shows the functional components of the THINK part.

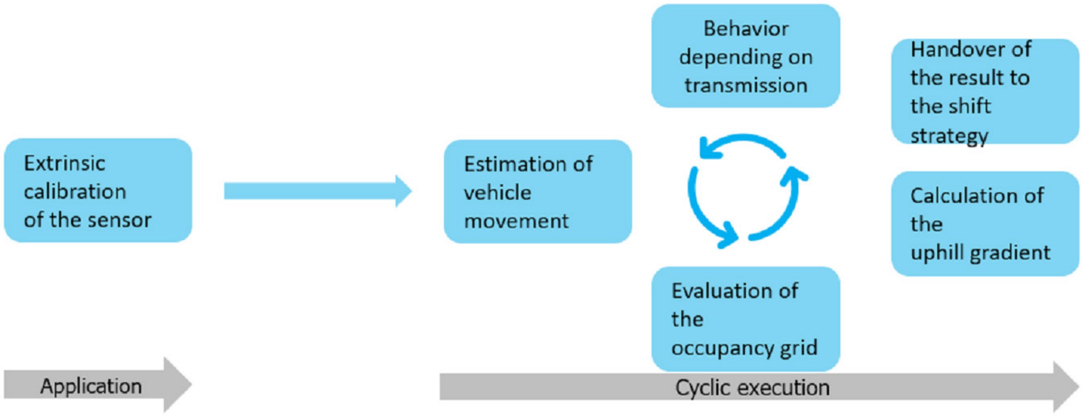

Figure 7: Representation of the functional components of the THINK part (© ZF Friedrichshafen AG)

Extrinsic calibration determines the position and orientation of the radar in relation to the vehicle. This is necessary for being able to evaluate the radar data accordingly and for determining the distances of uphill gradients to the radar (vehicle). This is done in the application. Figure 8 shows the acquired radar data in a ROS visualization. In this case, a video recorded by a camera was also shown to ensure a better comparison of the measurement data.

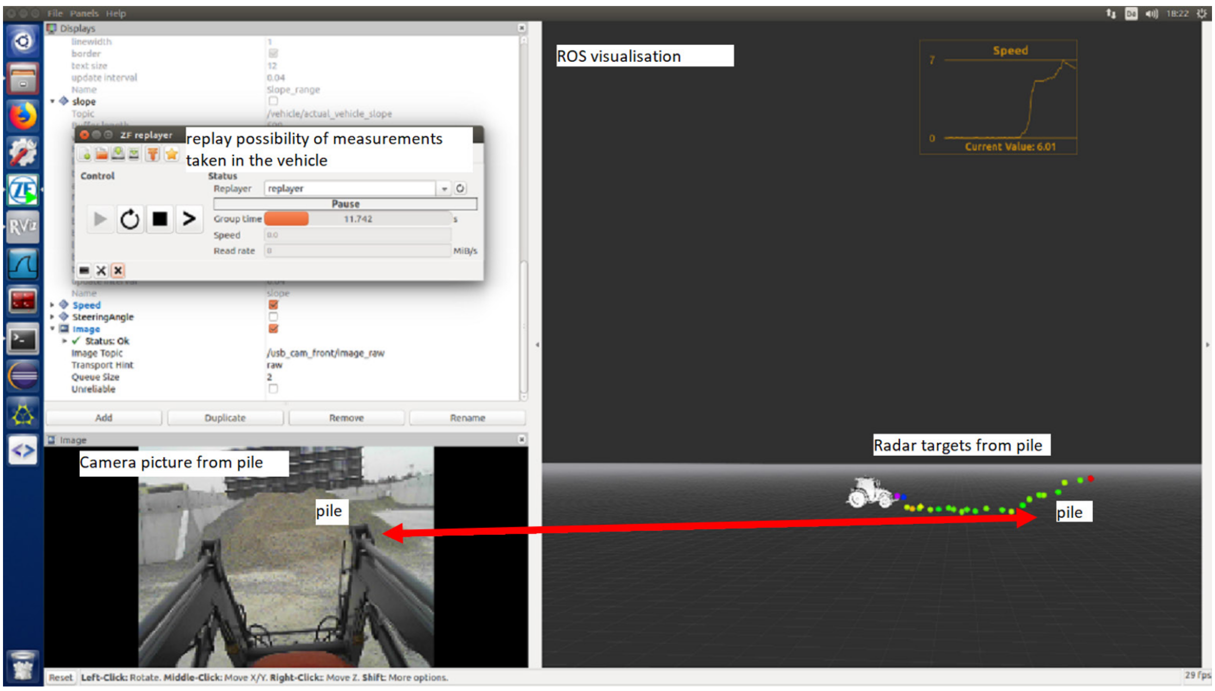

Figure 8: Visualization of the radar data in the ROS development environment (© ZF Friedrichshafen AG)

The second step involves estimating the movement of the vehicle, which is calculated using the data from transmission control, the steering angle, and the vehicle speed. The distance traveled since the last measurement can be determined on this basis. In the following, we will describe in greater detail how the angle and distance in relation to the uphill gradient are determined.

Calculation of the uphill gradient data using an occupancy grid

It is first necessary to note that the following example is based on the assumption that the uphill gradient in front of the vehicle, as shown in Figure 9, continuously slopes upwards.

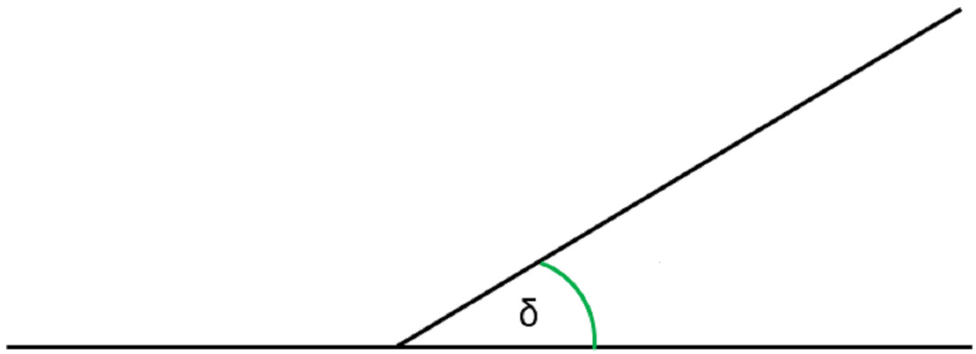

Figure 9: Angle of uphill gradient (© ZF Friedrichshafen AG)

The uphill gradient data (angle and distance of the uphill gradient in relation to the vehicle) are calculated using an occupancy grid [The Mathworks]. In this way current as well as historical radar points can be used to determine the uphill gradient data. The uphill gradient data can thus be calculated with a small number of radar reflections for each measurement.

As an example, an occupancy grid is shown in Figure 10. The values are plotted in such a way that the distance traveled is shown in the x-direction and the radar reflections recorded at the respective height are shown in the z-direction (as azimuth values due to the rotation of the sensor). Conceptually, the terrain in the direction of travel is intersected vertically (2D occupancy grid). Each cell in the occupancy grid is now assigned a defined size. In this example, it is 0.5 x 0.5 meters. The value in the respective cell is the accumulated value of the radar targets as detected in the cyclic radar measurements. The higher this value, the more reflections detected in this cell area.

Figure 10: Representation of the radar points in the occupancy grid (© ZF Friedrichshafen AG)

In order to be able to make use of the historical values when the vehicle moves, the occupancy grid is shifted by the distance traveled in the x-direction. In this way it is possible to arrive at a much more robust recognition of the uphill gradient. Data is shifted to other cells by evaluating the transmission output speed.

After that, the uphill gradient data is determined from the occupancy grid using a variety of different calculation methods.

One possible algorithm for calculating the uphill gradient data is explained below. The occupancy grid with a schematic representation of the determined uphill gradient can be seen in Figure 11.

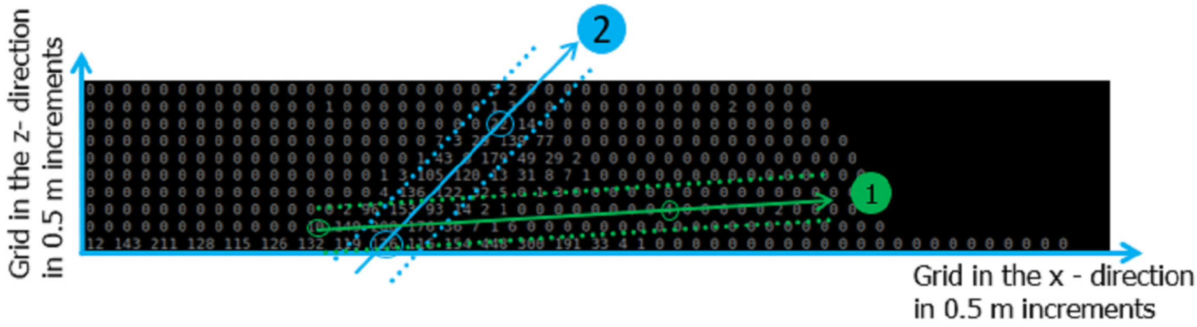

Figure 11: Determination of the uphill gradient data with an algorithm (© ZF Friedrichshafen AG)

Two cells (which are occupied) are selected at random, and a straight line is placed through them. Then the orthogonal distance of each occupied cell to this straight line is calculated. If a cell is occupied more than once, this distance is also counted in the multiple weighting. This step is then carried out several times with several different straight lines. The straight line that has the most other entries in its direct vicinity in the occupancy grid is selected. The maximum distance to the straight line (dotted lines) limits the vicinity area analyzed.

In the example, straight line 2 was selected. As the resolution of a radar sensor is not high enough to read the uphill gradient directly from the measurement, the previously described step is essential. In addition, measurements can also be falsified by “ghost targets”, which must also be removed from the matrix.

Then the uphill gradient of the straight line is calculated, together with its point of intersection with the x-axis. This intersection corresponds to the distance of the vehicle to the uphill gradient.

Upon completion of this step, determination of the uphill gradient is finished. The calculated uphill gradient data (distance and angle) is transmitted to the transmission control unit via the vehicle communication bus (CAN).

The ACT part is performed by transmission control. Here, the content of the transmitted CAN message (distance and angle of the uphill gradient) is evaluated, and the transmission and drive are prepared for the uphill gradient ahead of the vehicle in accordance with the previously defined parameters. This is accomplished by adjusting the current shift strategy (transmission ratio and input speed) while taking the environment into account through use of the radar sensor.

Figure 12 shows the crossing of the same uphill gradient twice using the example of a continuously variable transmission. The red lines show the uphill gradient crossing with the function activated while the blue lines show the crossing with the function deactivated.

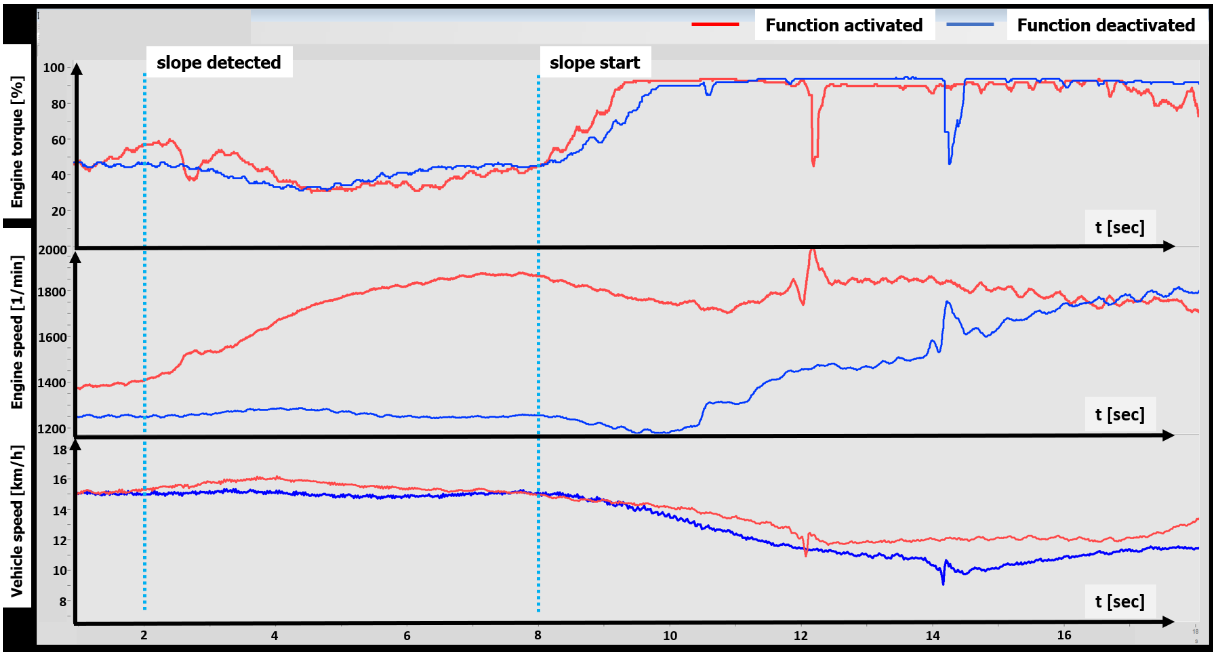

Figure 12: Representation of the uphill gradient recognition (© ZF Friedrichshafen AG)

Since the transmission in use enables a stepless transmission ratio, the engine speed can also be increased continuously, allowing for a higher power demand or a higher power reserve at the beginning of the uphill gradient. It can clearly be seen that the transmission control unit's response to the recognized uphill gradient now occurs earlier. In the red measurement, the change in transmission ratio takes place at second 12. In the blue measurement, the change in transmission ratio occurs two seconds later, at 14 seconds. Differences in engine speed when entering the uphill gradient are due to test execution. These tests were carried out one after the other without being able to set a fixed engine speed. It can clearly be seen that, when the function is active, the engine speed increases before the uphill gradient is reached, regardless of the output engine speed upon recognition of the uphill gradient. The transmission control unit increases the engine speed and adjusts the transmission ratio accordingly, and the vehicle speed remains at a higher level. Thus, the uphill gradient can be climbed faster. The drop in speed is significantly reduced.

Conclusions

This proof of concept was successfully implemented in a tractor and tested in an off-highway environment. For implementation of a predictive shift strategy, the results show that uphill gradient recognition using a radar sensor is possible. The quality of recognition could be further improved by adding an algorithm to compensate for the sensor vibrations that arise from the sensor being mounted on the vehicle. Higher resolution of the radar sensor would also improve the quality of the uphill gradient recognition. Since the recognition algorithms and the sensors are vehicle-independent, it would be possible to transfer this system to other vehicles.

The advantages of radar-based uphill gradient recognition are as follows:

- The efficiency or performance of the vehicle is increased through recognition of the environment
- The shift strategy is adapted to the situation

- The frequency of shifting operations is decreased
- Upshifting before uphill gradients is prevented
- Driving comfort is improved

The following might be added in the future:

- Determination of the actual vehicle speed (the speed over ground) in order to recognize and control wheel slip
- Use of algorithms from the automotive environment for object recognition with driver warning or brake intervention (in case of other vehicles, cyclists, pedestrians)

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