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IR Sensing Integrated with a Single Board Computer for Development and Demonstration of Autonomous Vehicle Following

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Dr. H. Bryan Riley, who joined Ohio University in 2010, has taught courses in signal processing, electrical communication systems, EE capstone design, electric machines, adaptive signal processing, and hybrid and electric vehicles. Riley, who spent his early career in the automotive industry, has managed multi-disciplined and global engineering teams responsible for introducing advanced electronic features on production passenger vehicles such as enhancements to vehicle stability control (VSC), adaptive cruise control (ACC), and other active safety features. He holds three patents and launched Provectus Technical Solutions, LLC, and engineering services company. Dr. Riley has implemented a Vehicle Modeling and Simulation Laboratory (VMSL) and current research interests include autonomous vehicle modeling and simulation, sensor fusion, parameter estimation, and machine learning.

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Abstract— Active learning occurs on different levels and we define a relevant problem for which students may achieve "hands-on" learning. The Infra-Red (IR) spectrum sensing for autonomous vehicle applications is a compelling approach to detecting objects in the path of vehicle travel. Official data indicates 90% of the primary factors behind crashes are due to human errors, 40% of fatal crashes involve driver alcohol or drug use, 20 % due to driver distraction and/or fatigue as per the National Highway Traffic Safety Administration, 2012. Therefore, Autonomous Vehicles (AVs) are predicted to reduce crashes and injury rates by upwards of 50%, versus non-AVs. Engineering educators are motivated to prepare students to contribute to transformative and highly beneficial technologies to support Intelligent Transportation Systems (ITS) and the future of the mobility industry. The design process for this project starts by researching various sensor technologies and applying them to a robotics/machine intelligence application. Such applications require efficient, reliable, and high performance sensors. The paper reports the rationale for selection of an IR sensor rather than ultrasonic sensors, RADAR, or a camera to perform the sensing function. Afterwards the team proceeded with the design, implementation and testing of an IR sensor configuration in conjunction with an embedded system to track a lead Remote Controlled (RC) scaled-model vehicle. A summary of the student's learning, test data and results are presented to suggest how IR sensors can meet stringent requirements for an autonomous vehicle sensing application.

Keywords: IR sensors, autonomous vehicles, self-driving vehicles, embedded systems

I. Motivation and Background

An established requirement for ABET accredited electrical engineering degree programs, includes providing a two-semester capstone project design experience. In a few cases, undergraduate electrical engineering students may undertake highly self-directed projects to engage learning about sensors, software design, and hardware development. One of these self-directed student projects considers the challenge of implementing a pair of remote-controlled (RC) small-scaled vehicles to investigate autonomous vehicles, related system design issues and operating performance. This is an important research project since "intelligent systems" are included in routine applications and incorporate multiple engineering disciplines. Development and integration of target tracking algorithms, software, and computing hardware for autonomous driving continues to mature advances occur in each of these areas. As part of the background and familiarization with current autonomous vehicle related technologies, the students reviewed consumer product literature including documentation on the Audi A4, Tesla Model S, and Chevy Bolt by GM, technical reports, along with many IEEE conference papers. Students became aware of many advanced systems that enhance safety, comfort, and convenience. The students proceeded to study current production autonomous vehicles and became aware of technologies such as 'traffic jam assist" which is an advanced implementation of 'Stop and Go" or low speed Adaptive Cruise Control (ACC) as depicted in Figure 1.0. Although robotics is a popular area, gaining hands-on experience to understand how sensors interact with the environment and recognize complex situations are project goals. Another goal was to implement vehicle following capability using a sensor set combined with an embedded computer on mobile platforms to demonstrate automatic following scenarios in indoor environments.

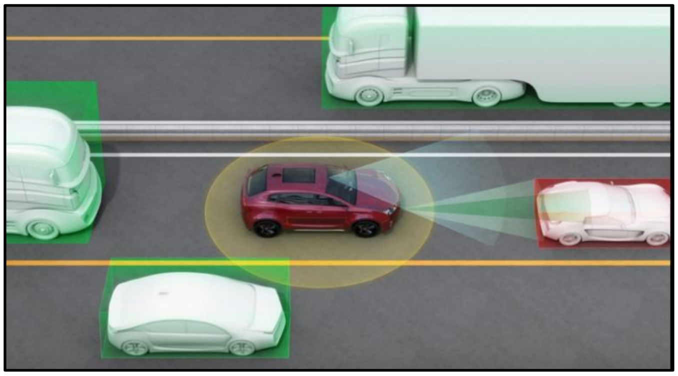

Figure 1.0 Illustration of stop-and-go and adaptive cruise control (ACC) technologies.

several related ideas into reality as well as explore additional principles of electrical engineering and in support of current and upcoming coursework assignments. A major premise for this work starts with development of as set of requirements for their autonomous vehicle by assuring safe operation while simultaneously exposing students to the hardware and software systems development process. During the early stage of the project, students defined requirements to accurately indicate the vehicle's location relative to any in path obstacles, whether static or dynamic and their position relative to fabricated road, lane markers, and edge boundaries. Students pressed forward to present and validate their engineering solutions to demonstrate achieve object sensing, autonomous mobile following and a user-friendly human-machine interface (i.e., joystick control of the target RC). The project continued by investigating related sensor technology systems and solutions that enable vehicle following. The host vehicle is defined to carry the sensors and a target vehicle travels in front as the surrogate vehicle. Guiding students that are enthusiastic to join innovative teams and contribute to advancing ITS solutions was rewarding and this project enabled them to gain experience, practice and practical problem-solving skills. Students were expected to study outside of assigned homework, consult with experts, obtain new as knowledge as necessary, and familiarize themselves on a practical level with circuit analysis, DC power, electric motors and microprocessors thus positioning themselves as engineering graduates with both "*hand-on*" and

Details of these technologies were received as

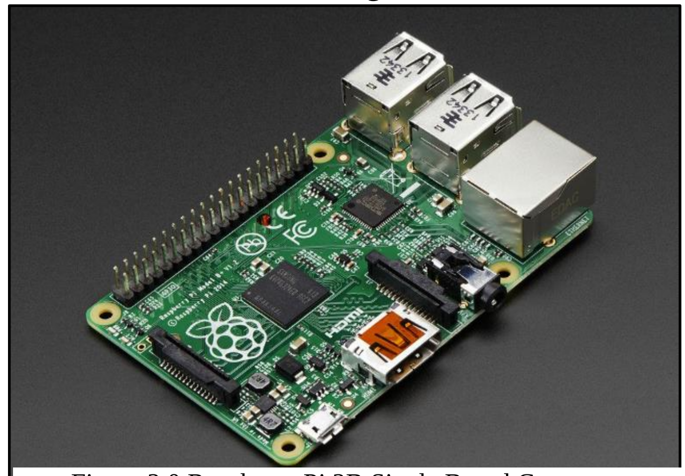

Figure 2.0 Raspberry Pi 2B Single Board Computer

intriguing by the students and motived them to turn practical experience. The following sections present details of the project including scope and a descriptive breakdown of project tasks. Engineering courses completed to date formed a solid basis. Their background in physics and mathematics was very helpful in technical selection of the sensor. Their background drove the identification of an infrared (IR) proximity sensor (i.e., λ = 870 ±70 nm). Electrical engineering knowledge is utilized to design and implement a system using the Raspberry Pi 2B single board computer, the I/O ports and its integrate functional capability within two remote-controlled (RC) vehicles. Upon incorporating design modification and electrical troubleshooting, the student ultimately demonstrated autonomous following scenarios using the above components. The Raspberry Pi 2B+ was selected for this project which is a relatively powerful and inexpensive single board computer including a GPU. It is shown in Figure 2.0 with interfaces for:

- Four USB 2.0 Ports,
- 24 Pin Header with GPIO, and
- Ethernet connection.

The Raspberry Pi 2 B+ is very popular as a selection for embedded applications due to its low power consumption and low price in comparison to its capabilities. Digital simulation was considered and the team elected to conduct a robust system design on paper before selecting and integrating physical parts. Student learning experiences continue with an implementation of the Raspbian Jessie operating system utilizing General Purpose Input Output (GPIO) capability to transmit/receive intra-vehicle messages. The system design requirements for selecting the IR sensors, configuring the GPIO ports and camera port as well as design of the power distribution circuit are further described as the total system design was completed. Additional project work ranged from designing a motor controller needed to achieve a smoother RC following behavior as the host RC tracked behind the lead RC. Typically, students are exposed to controls in at the junior level in electrical engineering curriculum and this work reinforced the course. As a result of self-study and other instructor guided learning exercises for the students, a proportional-integral (PI) control algorithm was designed and implemented in Python 2.7 software. This algorithm provides a more effective response and tracking-following performance over the bang-bang controller. Another aspect of the project involved students writing test procedures to collect test data and conduct an analysis that validates successful sensor integration and RC host to RC target vehicle following. Testing scenarios were defined to examine the performance of these embedded systems as the host and target vehicles perform maneuvers driven by a single joystick. Positive educational experiences occurred as the project enabled students to design a system that replicates an autonomous driving vehicle. Progress continued as an investigation into how well such technical solutions will be received for production vehicles that operate on public roadways, in dense traffic, and in dynamic driving conditions.

II. System Design and Architecture of Vehicle Sensing System

The sensing system design started with benchmarking and selection of a set of 3 Sharp infrared distance sensors. These sensors are incorporated onto the RC host vehicle as shown in Figure 3.0. In should be noted that the student review the physical dimensions, designed, and fabricated the mounting brackets that house the three sensors. The two outside sensors detect the turning direction of the host vehicle while the middle sensor detects the distance between the host and lead vehicle. In practice, as one of the outside sensors provides a very weak signal, which corresponded to little or no reflection, then correspondingly the opposite outside sensor provides a strong return of energy. This provided sufficient sensory information regarding the position of the host vehicle and more importantly the software determines that the lead vehicle had turned or changed direction of forward travel. As the host vehicle detects a turn the embedded system

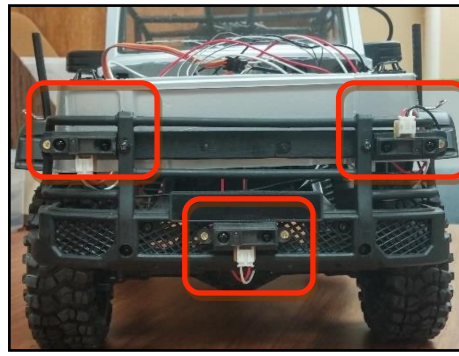

Figure 3.0 Configuration of the 3 Sharp IR sensors onto a HG P402 1/10 full scale 2.4G climbing car ragtop 4WD

transmits message to the motor controller to take an appropriate right or left. The duration of turning continues to occur until all 3 forward-looking sensors return to receiving energy levels which correlates to the target vehicle appearing in hindsight. The students experimentally determined these energy levels and the necessary thresholds required to

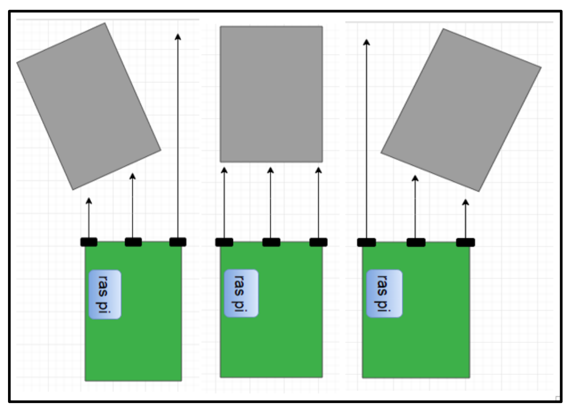

Figure 4.0 Sensor mounting and configuration for non-overlapping coverage conditions

successfully operate. The Raspberry Pi I/O ports and sensor interface wiring diagram describing this concept is shown in Figure 4.0. The wiring, soldering, and electrical continuity checks of the electrical sensor harness required trouble shooting and patience. Once again, the active learning and technical successes provided the students with a significant sense of accomplishment theory and practice became unified.

III. IMPLEMENTATION AND RC SCALED-MODEL VEHICLE BUILD

The next step of this project was to demonstrate reasonably good tracking performance by the host RC as it follows the target RC along the same trajectory and including a change in speed, acceleration or steering to the right or to the left. To test the control system, the host vehicle's DC motor controller receives commands from the Raspberry Pi Model B single board computer. To accomplish this Cytron Technologies MD10C 3.0, a hefty 15A motor controller with Pulse Width Modulation (PWM) capability, was selected as seen in Figure 5.0.

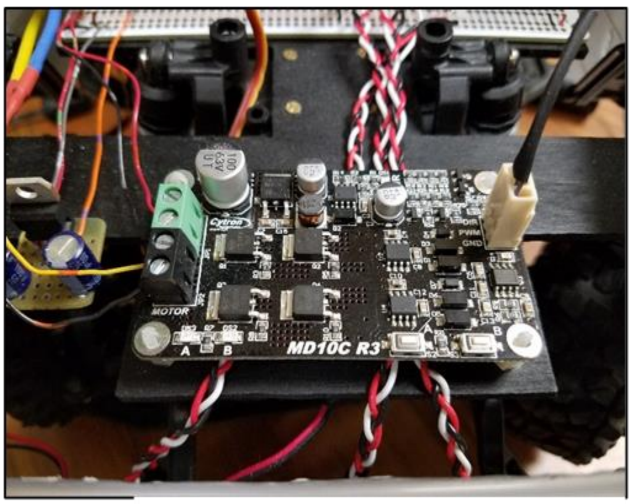

Figure 5.0 Motor controller hardware utilizing PWM capability

Based on a technical investigation, earlier engineering experiences, and after smaller 5A motor controllers experienced thermal failure, the requirement was re-scoped accordingly. Once the proper motor controller was purchased, the next issue was the steering servo. The steering servo needed power as well as a control signal which could both come from the Raspberry Pi. Considering the longevity of the Raspberry Pi, a 5-VDC voltage limiter circuit was designed and built. This voltage limiter was then connected in parallel to the 7.4-VDC battery and the DC motor, which allowed the servo to be powered off the more robust and replaceable 7.4-VDC battery. The hardware block diagram is provided in Figure 6.0. Upon interfacing power and on/off switching, the control system was developed, tested and validated. The initial control strategy consisted of implementing bang-bang control system where no change happens until an upper or lower limit is obtained. This approach ensured the system would operate within the design limits. The students then appealed to their mechanical engineering ingenuity for the attachment and packaging of 3 IR sensors on the front of the host vehicle. Initially the sensors were attached with the same orientation which caused anomalies in the software. These anomalies were caused by the sensors slightly skewed IR beams. Upon troubleshooting this technical issue, the sensors were oriented that each corner beam provided coverage of the corners of the lead vehicle effectively. The final solution consisted of orienting the sensors such that, the middle sensor was placed at a lower elevation level on the front of the RC vehicle so that its beam did not interfere with the readings from the two corner sensors. This was a very important engineering experience for the students, relative sensor placement and energy returns from passive sensing. Upon proper placement of the sensor, an investigation for the programming language was conducted. Software language Python 2.7, released in 2010 and utilized by numerous technical persons, was selected because of its attractiveness for interfacing to the hardware through the Raspberry Pi Model B single board computer. Additionally, Python was chosen because it is a straightforward language to learn and due to project timing constraints, it supports flexibility and portability for future students to continue this research project. The students rapidly became proficient with programming in Python and the on-line examples and support was excellent. Upon configuring the sensors and programming the control software as a bang-bang control algorithm, the

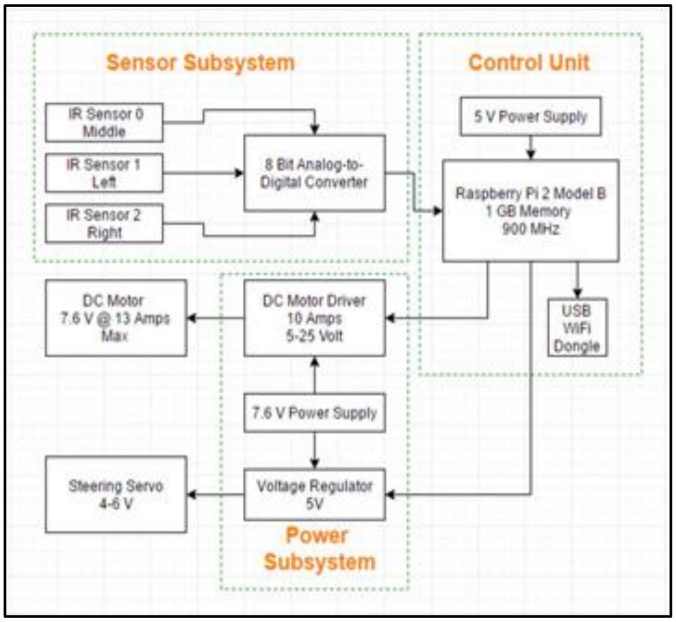

Figure 6.0 Hardware block diagram

students could begin development. It is important to note that team discussions were held on a regular basis regarding the progression of the project. To that end, phase one of the algorithm is designed so that if the left sensor readings are below a threshold, ε_t, then turn the front wheels to the max right angle. When the right sensor readings occur below ε_t then turn the front wheels to the max left angle. If both sensors are above ε_t then the motor control for front steering of the wheels guides the RC vehicle along a straight-line path. This approach was logical, promising and effective in many ways (i.e., quick processing, easily implemented, etc.) however its forward travel was somewhat "choppy" and would cause the host vehicle to weave back and forth behind the lead vehicle. As an engineering team, along with faculty consultation, the students concluded the performance was not acceptable for a prototype platform to serve for investigation into sensing methods of self-driving cars in real-world applications. Referring to classical control system theory the team elected to develop and apply proportional control. In this approach the feedback, is in proportion to the degree the system diverges from the ideal point. This approach is realistic and has been implemented in commercial products. The approach was to develop two proportional-integral (PI) control algorithms for this project. Proportional-integral control algorithm design starts by setting a desired set point to maintain the host vehicle following at 20cm behind the lead vehicle. Then the acceleration of the vehicle is based off the error or distance from this set point. The farther away from the set point the host vehicle is, then acceleration will be more aggressive. Then when it approaches the set point the acceleration slows down to a constant velocity. This simple example is exactly what was implemented for the speed-control PI algorithm. The steering-control PI algorithm "took more work to develop". To start off, the right outside sensor reading was subtracted from the left outside sensor reading. This would result in either a positive or a negative value which indicated whether the lead vehicle had turned right or left respectively. Just as

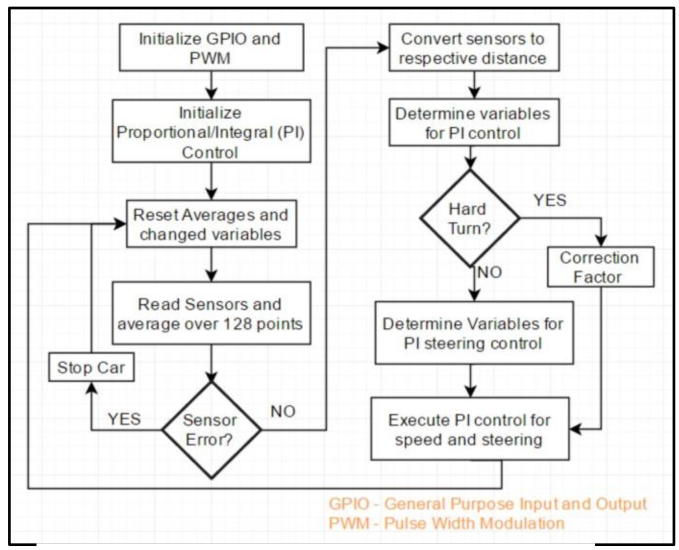

Figure 7.0 Software flowchart diagram

with the speed control, if this difference grew larger, the host vehicle would turn harder. As system integration work continues, the host vehicle repeatedly loses the ability to follow or track of the lead vehicle when a turn radius greater than 17^{o} is issued. This issue led to the development of a dynamic PI control algorithm for the steering control. In this algorithm, when an outside sensor and the middle sensor begin to miss the lead vehicle; this implies that the vehicle is making a turn radius of 17^{o} (i.e., sharp turn) or greater. To compensate for this sharp turn, the PI control algorithms combine and dynamically reconfigure the sensors used for control. The speed PI control is shifted to the outside sensor since it remains in contact with the rear of the lead RC vehicle. The set point of the speed PI loop is then decreased to compensate for the smaller inner radius of the turn. The steering PI control turns the wheels all the way to one direction and uses the difference between the middle sensor and outside sensor to detect the severity of the turn. Once the target vehicle maneuvers out of a sharp turn and the host vehicle IR sensors return to receiving non-cluttered readings for the intended field-of-view (FOV) and the PI control reconfigures back to the initial state. This addition of dynamic PI control significantly increases the host vehicles following performance. The flowchart corresponding to the software implementation is depicted in Figure 7.0.

IV. DATA COLLECTION AND ANALYSIS

Performing trial runs with the IR sensors and PI control loops there continued to be jolting movement from the host vehicle as it followed the target vehicle. The engineering judgement was that the IR sensors were not reading linearly and therefore at different distances, the host vehicle produced erratic following movements. The generalized mathematical relationship between distance and output voltage reading is given by Equation 1:

$$d = \left(\frac{1}{(a * A_{DC} + b)}\right) - k \qquad (1)$$

where: d – distance in centimeters
k – corrective constant
A_{DC} – digitized value of voltage
b – free member (value determined by the trend line equation)
a – linear member (value determined by trend line equation)

For example, the change in sensor reading from 5 cm to 10 cm was much greater than the change in sensor reading from 30 cm to 35 cm. To account for the non-linear characteristics of the IR sensors the students needed to develop an approximate exponential curve that was best fit. To do so, students placed the host RC at different distances ranging from 10 cm to 40 cm while measuring the sensor output. Once this was finished the students graphed the results in Microsoft Excel which can been seen in Figure 8.0. Measurement data in the spreadsheet is used to calculate an exponential trend line and is given by Equation 2:

$$d = 43{,}300x^{1.236} \qquad (2)$$

where: d – actual distance in cm.
x – sensor reading

The students then incorporated equation 2 into their algorithm, converting the arbitrary sensor readings into real distance values. This led to the errors being generated in the PI loop to be linear with the distance and the control system's performance improved dramatically.

V. SUMMARY AND CONCLUSIONS

Per team discussions, engineering development activities, troubleshooting and study sessions, the students have consistently expressed their enthusiasm for the active learning and practical experience gained by working on this project. There has been both breadth and depth in investigating the capabilities of IR sensing for autonomous vehicles. Prior to start, neither of the electrical/computer engineering undergraduates had significant practical experience in embedded systems and only course homework assignments in hardware programming. Technical experiences were gained as well as managerial and invaluable teamwork experiences. The process of starting a research project and seeing it through has many moving parts which the team was unfamiliar with but can now say they understand as they continue to learn. With limited knowledge and low cost sensors, the students successfully designed and implemented a functional host vehicle-to-target vehicle following system. Additionally, the students were able gain experience with the design process steps and build teamwork skills prior to taking the required EE the capstone course. Plans are to continue this project and investigate related performance and tradeoff matters associated with

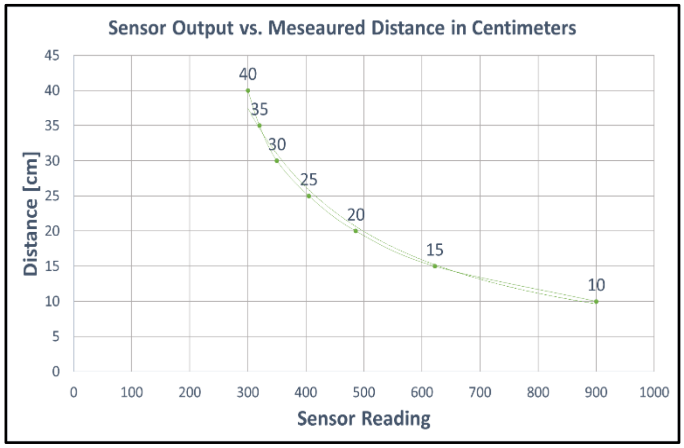

Figure 8.0 Sensor Output vs. Distance [cm]

more sophisticated sensors, vehicle control, and target recognition and identification. Longer term goals shall include replicating real-world environmental conditions (i.e., fog) for testing and analysis of the "lead vehicle" and "sensor vehicle." The students continue to be enthusiastic regarding this project and interested to investigate more complex sensing techniques. An approach consists resolving distances based on the speed of light by measuring the time-of-flight (ToF) between the sensor and the targeted image using a ToF Camera or remote sensing via Light Detection and Ranging (LIDAR).

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