

SUBAH – Hydrogen powered SUBA

João Graça

Instituto Superior Técnico, Universidade Técnica de Lisboa, Lisbon, Portugal
email: joao.da.graca@ist.utl.pt

Abstract – This paper presents a hydrogen fuelled demonstration system based on a 1:10 scale model car. The vehicle, called SUBAH, is powered by a Proton Exchange Membrane (PEM) hydrogen fuel cell, in combination with two ultra-capacitors. It's self-guided by using two coils to sense a magnetic field generated by a current carrying wire along an acrylic track. It has a rear-wheel electronic differential with two independent DC motors, and a servo motor for steering. This system is to be displayed on Instituto Superior Técnico – Taguspark.

Keywords: *Hydrogen fuel cell, ultra-capacitors, self-guided, magnetic field.*

I. INTRODUCTION

The emergent energy need is one of the problems that made XX Century society dependent of petrol and their derivatives. Petrol price fluctuations have been stimulating the search of ne energy sources. The interest in renewable energy sources (wind power, hydric, photovoltaic and geothermal) is rising, as a result of the awareness about the consequences of the emission of pollutant gases into the atmosphere. The need of transporting potential energy according to the needs of mechanical or electrical energy in vehicles, high production costs, rapid deterioration and poor battery performance, make the use of hydrogen a possibility in the near future.

Hydrogen is the simplest substance that can be found, being the first element of the periodic table. It has the highest amount of energy per unit weight, this being the main reason for its use in space programs, where weight is crucial. It is also noteworthy that hydrogen has about 2.5 times the power of a hydrocarbon fuel (petrol, diesel, methane, propane, etc. ...).

A. Objectives

This work aims to raise people's awareness of an alternative to traditional fuels, the use of clean energy for transportation vehicles and their potential.

For this purpose a hydrogen fuel cell is used to perform the conversion of the energy released by the reaction of hydrogen and oxygen into electrical energy. Being pure water the only product of this reaction, it presents itself as a clean alternative.

The goal of this project is to develop a small electric demonstration vehicle called SUBAH, mainly powered by the electricity generated by the hydrogen fuel cell, with the appropriate sensors and actuators to move along a transparent track presented in Figure 1. This track was previously built at

Instituto Superior Técnico as part of a final course project [1]. It's mainly composed of acrylic, comprises twelve poles with the possibility of lighting.

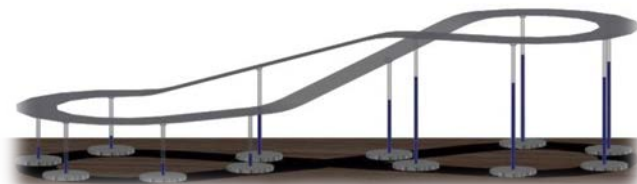


Fig. 1. Built acrylic track.

The name SUBAH is an acronym, influenced by the Portuguese phrase “Seja Um Bom Aluno” that means “be a good student”, and is also based on the 1:10 scale racing car model of a Subaru Impreza WRX. The addition of the letter H comes from Hydrogen.

B. State of Art

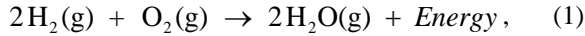
Hydrogen can be produced from diverse domestic feedstocks using a variety of process technologies. Hydrogen-containing compounds such as fossil fuels, biomass or even water can be a source of hydrogen. Thermochemical processes can be used to produce hydrogen from biomass and from fossil fuels such as coal, natural gas and petroleum. Power generated from sunlight, wind and nuclear sources can be used to produce hydrogen electrolytically. Sunlight alone can also drive photolytic production of hydrogen from water, using advanced photo-electrochemical and photo-biological processes [2].

Although hydrogen gas has a good power vs weight ratio, it also has a weak energy / volume or density [3], worsening its transport and volume occupied. Even in liquid form, obtained with huge energy costs at temperatures of -250 °C and pressures of 700 bar, it has about four times less energy per volume than gasoline, requiring a tank with resistance to high pressures. Thus, for the same amount of energy, a hydrogen tank will be heavier than a conventional gasoline tank. However there are ways to avoid this, hydrogen can also be stored chemically with metal hydrides, composed of foamed matrices that have the capacity to absorb and release hydrogen at low temperatures and pressures, resulting in a safer storage. There are already companies, as Horizon [4], selling hydrogen "batteries" using metal hydrides, to use with the devices they sell.

Hydrogen can be used to produce electricity, using fuel cells, converting chemical energy into electrical energy

passing the hydrogen and oxygen molecules through an electrolyte producing water.

The total reaction is



where the energy generated is both electrical and thermic.

There are various types of fuel cells, based on their temperature operation and electrolyte type [5]. Today PEM (Proton Exchange Membrane) fuel cells are widely considered to be the most versatile of currently available technologies [6]. The electrolyte in these types of fuel cells is made of a polymer membrane that lets through hydrogen protons, forcing the electrons to travel through the conductive layer to the circuit.

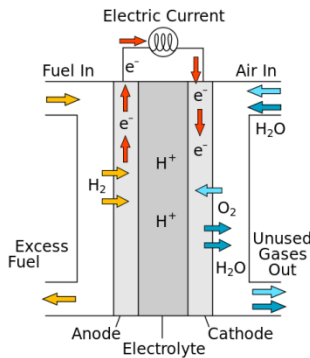


Fig. 2. PEM fuel cell [7].

In Figure 2 is presented the overall electrochemical process of a PEM fuel cell. This type of fuel cell operates at low temperatures, between 30 and 80 degrees Celsius, and its efficiency is around 40 %.

II. DEVELOPMENT

A. Motion

Since this is a demonstration system, in order to observe the various sensors and actuators used, much of the structure of the vehicle was built in transparent acrylic.

For the steering, because of its simplicity, a servo-motor was used, resulting in a digitally controlled steering angle.



Fig. 3. Servo-motor steering.

To avoid the construction of a mechanical differential, it was placed a traction motor for each rear wheel, enabling

independent control of the speed relative to the steering angle, resulting in an electronic differential.

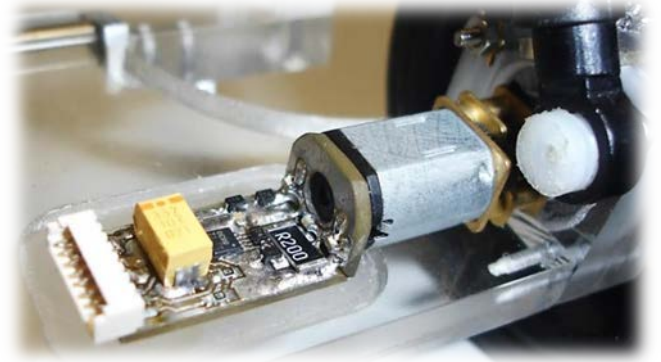


Fig. 4. Independent rear wheel motor.

Not requiring a high speed, small DC geared motors were used. At 5 V, they rotate at a speed of 50 RPM and can deliver 0.5 N.m of stall torque. To drive each DC motor, the DRV8830 [8] H-bridge from Texas Instruments was used. This integrated circuit controls the average output voltage by changing the duty cycle of the PWM output wave. The major advantage of DRV8830 is that both the duty cycle and direction of the output is digitally controlled with I²C, a two wire serial communication, while in conventional H-bridges the PWM needs to be externally generated.

In order to have a small friction, a ball bearing was placed in the hubs of each rear wheel, along with a slotted encoder disc to measure the rotational speed using an infrared LED and phototransistor.

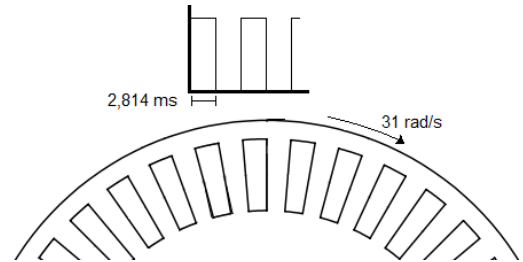


Fig. 5. Relation of the speed and slot pulse duration of the encoder

For the speed, it was implemented a P (Proportional) controller. This is a feedback controller, i.e., calculates the error between the measured and reference value and tries to minimize it by adjusting the process inputs, in this case the DC motors. The response of this controller can be adjusted with one constant - its gain K_g . The greater its value the faster the system responds to correct the error, but greater the overshoot.

The controller was implemented by a Microcontroller (MCU) and the gain K_g was scaled for a smooth yet fast response to speed variations. The chosen speed was 0.1 m/s or 3.1 rad/s, so that it is possible to observe the various

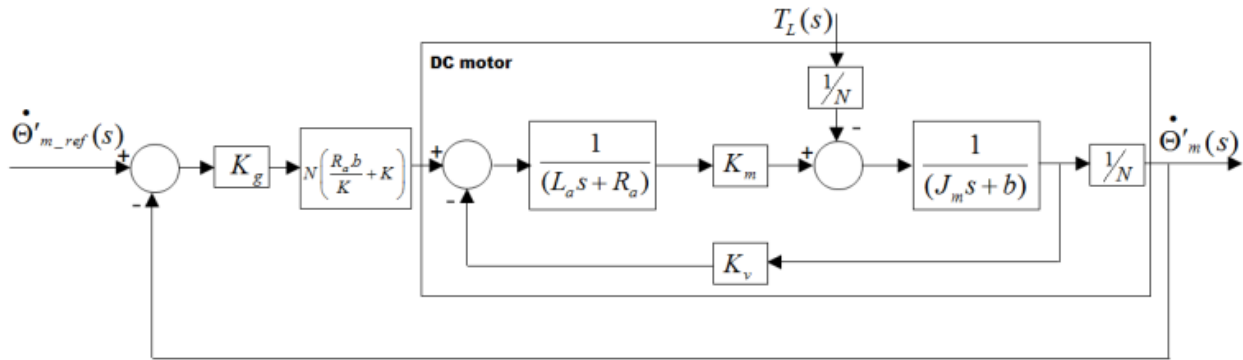


Fig. 6. Implemented speed P controller.

mechanical systems in operation. At this speed the car takes 1 minute and 50 seconds to do a full lap on the track.

For the vehicle to follow the track, a wire was placed along the center of the track, and by applying an alternating current, it would generate a magnetic field. To sense this magnetic field two inductors were built in the front of the vehicle, so that the voltage induced on them by the alternating magnetic flux would correspond directly to the deviation from the center of the track.

To generate the magnetic field on the track, the known 555 timer IC was used. The circuit was designed to output a positive square wave so that the 1st harmonic of the current signal in the wire would have an amplitude of 150 mA.

To have more sensitivity, a capacitor was placed in parallel with each inductor to create a resonant circuit in the frequency of the current carrying wire in the track. The value of this capacitor was such that its reactance was equal to the inductors at that particular frequency, resulting in a theoretical infinite impedance. As any wire, the inductor wire also has a certain resistance, and it is that resistance that limits the total impedance peak at the resonant frequency of 100 kHz. With this resistance, we can calculate the quality factor of the circuit, which is 28, and the bandwidth which is 3.6 kHz.

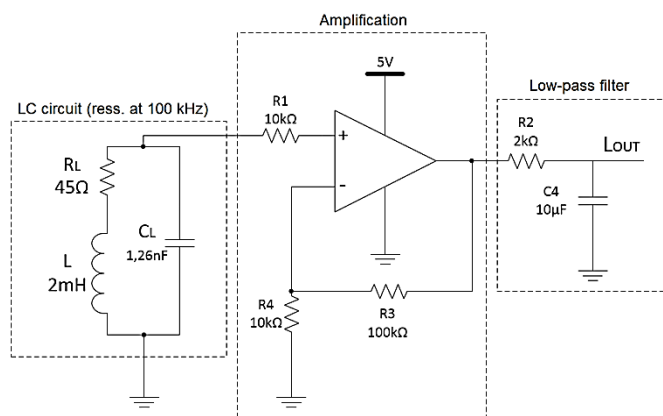


Fig. 7. Circuit for magnetic field sensing.

The induced voltage at the inductor is then amplified and half rectified with a gain of 21. It then passes through a low-pass filter, resulting in the average value of the amplified half sine wave.

The voltage difference of the two equally spaced inductors corresponds to the deviation of the center of the car to the center of the track, resulting in the measured relation of Figure 8 for different heights.

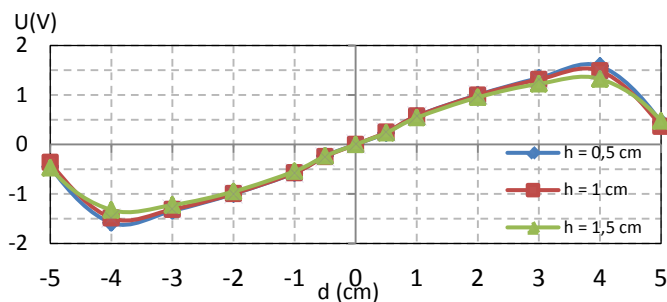


Fig. 8. Measured voltage difference between the two inductors at different heights from the track.

It's noticeable in Figure 8 that the relation between deviation and voltage difference is rather linear between 4 and -4 cm, facilitating its implementation on a MCU.

With this relation it was implemented a PD (Proportional Derivative) controller for the steering, the derivative is associated with the prediction of future errors based on variation of the error and is used to smooth the overshoot created by the P.

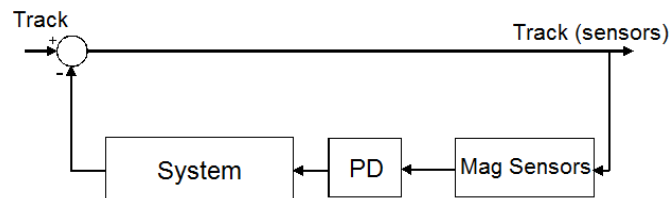


Fig. 9. PD controller for the steering system.

In the implementation of this controller it was taken into account the maximum speed of the servo-motor and the mechanical limits of the steering structure.

B. Energy Management

As said earlier, PEM fuel cells are the most versatile, so in this project a small 12 W PEM fuel cell was chosen. The cell used is the H-12 model from Horizon [9]. It comes incorporated with a fan to force the air through the slots and in addition to the hydrogen input, it also has an outlet to purge any air that is inside, giving rise to the hydrogen which in turn initiates the operation of the stack.



Fig. 10. H-12 model 12W PEM fuel cell from Horizon.

This fuel cell operates at a maximum temperature of 55° Celsius and at 0.55 bar of hydrogen pressure, it's capable of delivering 12 W of power at 7.8 V and as an efficiency of around 40 % at full load.

Being a demonstration system, it was chosen that the hydrogen would be compressed in the vehicle. This was accomplished with two syringes, operating as pistons, and a motor rotating a lead screw to convert its rotating motion into linear motion on the pistons, thus compressing the hydrogen.

To monitor the pressure an integrated pressure sensor was used, that gives a voltage corresponding to the sensed pressure.



Fig. 11. Designed compressor with two pistons and a lead crew.

Taking into account the motor maximum torque, a maximum hydrogen pressure of 0.35 bar was chosen. Testing the fuel cell with different loads resulted in the power curve of Fig. 12.

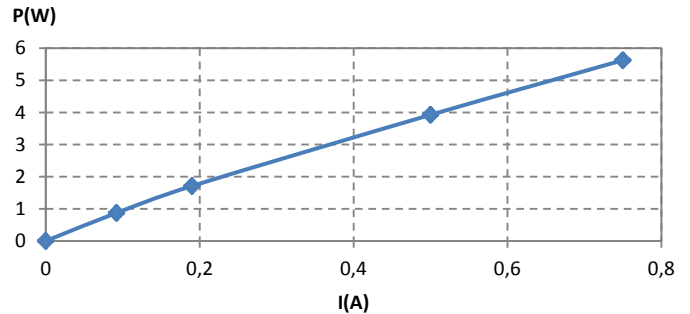


Fig. 12. H-12 Fuel cell power curve at 0.35 bar of pressure.

Calculating the relation between the electric energy output and the energy value of the consumed hydrogen in a period of time, it was possible to define the fuel cells efficiency curve in Fig. 13.

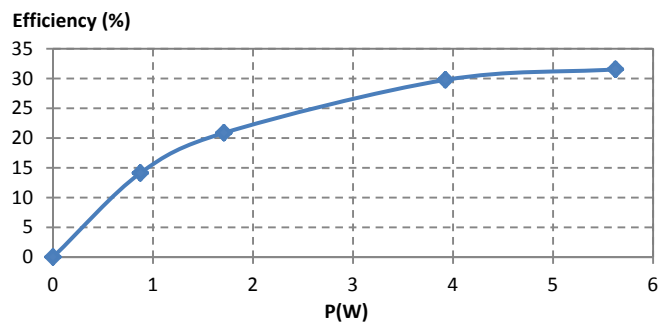


Fig. 13. Measured efficiency curve of the fuel cell.

It is important to relate the Fuel cell output power with the hydrogen flow rate. This is displayed in Figure 14.

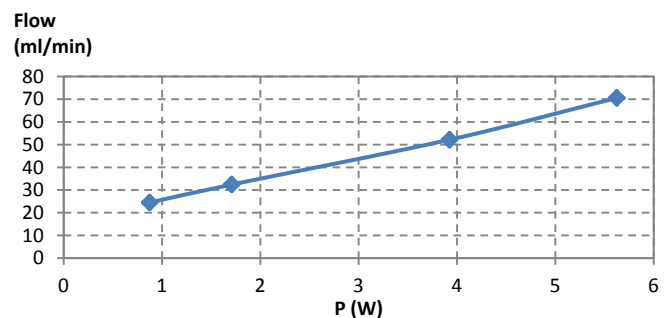


Fig. 14. Measured hydrogen flow rate with different loads.

Because the efficiency is greater at greater loads, a hybrid system with two series ultra-capacitors (UC) was implemented for energy management. These act as an intermediary energy tank between the fuel cell stack and the vehicle electronics, being capable of delivering transient power. When the ultra-capacitors voltage falls below a

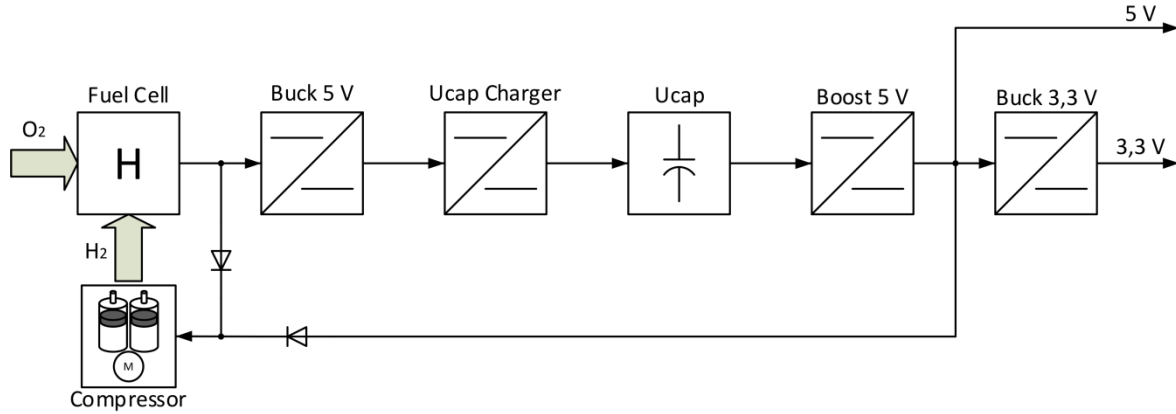


Fig. 15. Energy conversion system.

certain value the fuel cell starts to charge them at a fixed current, taking advantage of the high loads fuel cell efficiency. To balance and control the UCs charge, the dedicated UC charger LTC3625 from Linear Technology was used. This integrated circuit is a switching UC charger that as an efficiency of 85 %, and has a maximum input voltage of 5.5 V.

Because the voltage of the fuel cell varies from 10 to 7.8 V it was necessary to use a DC-DC converter, the TPS56528 from Texas Instruments, to down-convert the voltage to 5 V, which is within the range of supported voltages in the UC chargers input. This converter is highly efficient (about 95 %).

The maximum speed of the compressor motor directly affects the maximum hydrogen flow capability, so, when the fuel cell starts, the motor ceases to be powered from the 5 V power supply and becomes directly powered by the fuel cell at higher voltages, increasing its speed.

The voltage of the two series UCs varies from 0 to 4.8 V, because of this, it was also necessary to implement another DC-DC converter, the TPS61032 from Texas Instruments, to up-convert the voltage to a fixed 5 V, to power the motors and some other ICs. This converter also as an efficiency close to 95 %.

Some of the ICs operate at a voltage of 3.3 V, like the MCU and the speed sensors, so a low current DC-DC converter was placed after the fixed 5 V to down-convert it to the desirable voltage, with an efficiency of 90 %.

Multiplying all the converters efficiencies, the total conversion efficiency from the fuel cell to the fixed 5 V rail is 77 % and to the 3.3 V is 69 %. Taking into account a 30 % efficiency of the fuel cell stack, the overall efficiency from the hydrogen to the final voltage rails is around 22 %, neglecting mechanical losses in the compressor.

The measured average power consumption of the SUBAH on different situations is described in Table I.

Table I
Power Consumption

All stop MCU in sleep	150 mW
All stop wake MCU	400 mW
Filling the tank	800 mW
All systems running	4.5 W

The hydrogen tanks has a capacity of 200 ml, but the initial compressing, purging, and compressing again, leaves us with an effective hydrogen capacity of 110 ml. Analyzing the hydrogen flow rate in Figure 14 and taking into account the vehicles power consumption of 4.5 W with all systems running, it is easy to conclude that we have up to two minutes of hydrogen power operation.

C. Software

The MCU selected for the digital control of this system was the PIC24FJ256GB206 from Microchip. This model is particularly versatile in terms of peripheral configuration, it as a low consumption of 20 mW at an operating frequency of 8 MHz, and it has sufficient inputs/outputs to be left unpopulated for future development. It has a 16-bit architecture, with each instruction executed in two clock cycles, it has an analog-to-digital converter (ADC) of successive approximations (SAR) with 10 bit resolution with a maximum acquisition rate of 500,000 samples per second, which is more than enough to read the DC signals from the various devices, as the pressure sensor, the two magnetic sensors and the UC and Fuel cell voltages.

The only user interface to control the SUBAH are two buttons at the rear of the car, one to start the hydrogen charging, called "H2", and another to initiate motion, called "START". The two buttons also perform as an emergency stop of all the actuators.

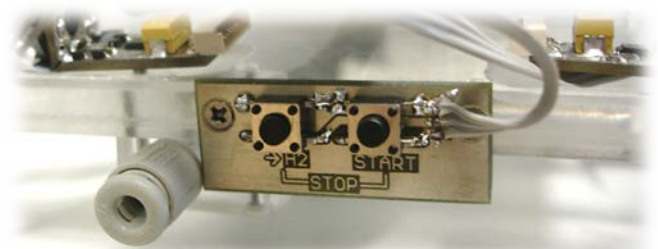


Fig. 16. Two rear buttons to charge and start the car, along with the hydrogen input.

To perform the function of each button, the user has to press it at least 3 seconds and then release, less than that and

the MCU will read it as an emergency stop, as long as the car is charging or running. When the car finishes the lap, emergency stops or the tanks become empty, if the fuel cell is running, the purge valve is opened to safely stop the fuel cells operation. Without this, the fuel cell would continue to use the remaining hydrogen from the tubes, eventually creating a negative relative pressure, damaging the membranes.

Another safety measure is the minimum magnetic field detected by the ADC, if it's detected that the signal is below a certain level, the car is stopped to prevent it from falling down the acrylic track.

When the car enters emergency mode or finishes the lap, after the purge valve is opened, the MCU is put in sleep mode to save energy.

III. CONCLUSIONS

An automated hydrogen powered model car was developed, to raise awareness about efficient alternatives to fossil fuels.



Fig. 17. Built SUBAH.



Fig. 18. Built SUBAH with transparent cover.

The use of ultra-capacitors as an intermediate energy storage between the fuel cell and the system enabled a better use of the hydrogen energy, since the fuel is used more efficiently with higher loads.

We can conclude that a magnetic field is a good way to follow the track without impairing its overall look. It has been found that the use of coils specially constructed for this purpose is the best way to detect the magnetic field. Since it is resonant at the frequency of the magnetic field it becomes very sensitive.

The implementation of a rear-wheel drive with each wheel moving independently with DC motors and the use of a servo motor for the orientation of the front wheels, brings great advantages in terms of speed control in curves.

The use of transparent acrylic, besides offering good resistance to mechanical stress, is the best option for any demonstration system in which its intent is to show all the sensors and actuators in action.

Future work proposals include an improvement of the speed measurement, suggesting a quadrature reading of the encoders. It is also suggested the implementation of RGB LED illumination in each acrylic pole of the track, controlled by an infrared communication with the car, using the expansion ports left on the MCU. With this communication there is the possibility of creating a computer program showing all the sensor values and events happening of the SUBAH.

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