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Determination of the velocity of a body moving uniformly

Inertial and relative velocities

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Abstract

In this paper, in the absence of forces we show how it is possible calculated the velocity of a moving uniform and rectilinear body without use external benchmarks. This is done using photodetectors that measure the arrival time of light from a point internal source to fixed equal distances inside the body.

We also show how the velocity of two arbitrarily chosen bodies with no forces acting on its and moving uniformly in a straight line can be found without the presence of other reference bodies. For this purpose, in addition to internal light signals, additionally, each of the bodies sends an external light signal to the other body and measures the arrival time of the reflected signal. The postulates in the special theory of relativity are used, that space is homogeneous, isotropic and that the speed of light in a vacuum is an invariant that does not depend on the speed of the radiation source.

Keywords: speed of light, speed of motion, inertial coordinate system, special relativity, STR, time, distance, light front, point light source, invariant, relative velocity, inertial velocity.

1. Introduction

According to Einstein's special theory of relativity (STR), the speed of light in a vacuum is an invariant constant that does not depend on the speed of the emitting source, and it is the maximum possible speed of interactions. The value[1] of the speed of light is C = 299 792 458 m/s.

Moreover, time is not common to all systems. This concept indicates that time is analyzed differently in classical mechanics, according to which there is a single (absolute) time for all inertial reference systems[2]. In order to use uniform time in the article, when determining inertial velocity we will consider motions relative to only one inertial system. We refer to the fact that at any point in a homogeneous and isotropic space, the light front generated by a point source is always a sphere. The shape of the light front does not depend on the speed of the source, since the speed of light is an invariant[1,2].

All bodies have individual quantities of motion which they preserve in the absence of forces or influences acting upon them. These bodies move by inertia uniformly and in a straight line. Each force pulse applied to them changes their individual amounts of motion to new values. Traditionally, when considering the motion of two bodies, we conditionally accept one body as stationary or determine the movement of the bodies relative to a third body, which we assume to be stationary. In this way we determine the relative velocity between the two bodies. When measuring the relative velocity, we require that the clocks of the observers in the two bodies are synchronized in advance. Here we will consider in more detail the inertial motion of absolutely rigid bodies.

In the description, it should be noted that the speed of light C and the speed of motion of the inertial system V are vectors.

2. Propagation of a light signal from a point source in an inertial system

The setup of the virtual experiment is shown in Fig. 1. An observer O and a point light source S are firmly located at the center O of an inertial rectangular coordinate system K with Axes X, Y and Z. The coordinate system moves uniformly with a speed V in the direction of the X-axis.

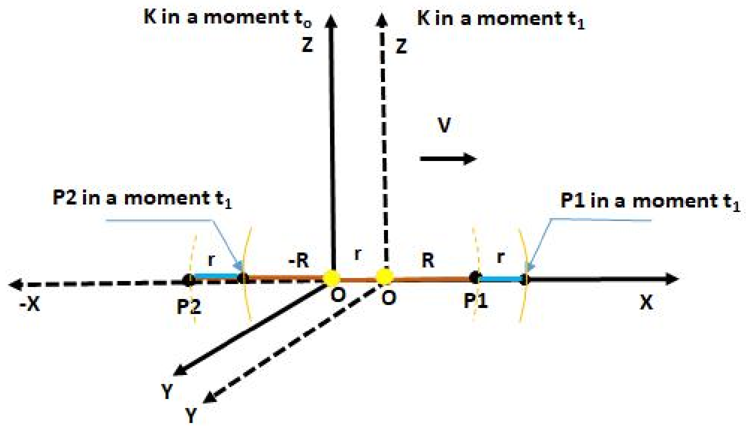

Fig. 1. *Observer O and a point light source S, which are firmly connected to the origin O of a rectangular coordinate system K, moving at a speed V*

Two identical photodetectors with memory are mounted on the X-axis at Points P1 and P2 at equal distances R and –R from the center O, respectively. Both photodetectors have built-in precision clocks and can accurately register the time when a light signal reaches them[4,5].

The time t flows in the same way in System K along the +X-axis and along the -X-axis regardless of the value of the speed *V*, according to the STR[3].

If at time $t_o = 0$, the clock of the observer and the clocks of the photodetectors are synchronized and at this moment we turn on the light source S, then, since the speed of light *C* is invariant and does not depend on the speed of its source, it will pass the distance R in both directions –X and +X over the same time t [6].

$$t = \frac{R}{C} \quad (1)$$

At the same time t, the coordinate system K will pass in the direction of *V* a distance of

$r = Vt$.

Then, the observer O, Point P1 and Point P2 will be shifted by a distance + r from their initial position. To reach Point P1, the light front will have to travel a distance R + r, and to reach Point P2, the light front will have to travel a distance R - r.

Therefore, the light signal will arrive at Point P1 after the following time:

$$t_1 = t + \frac{r}{C} = t + \frac{V}{C}t = (1 + \frac{V}{C})t$$

However, in an inertial coordinate system, the time that the light reaches Point P1 at a distance R located in the direction of its motion with velocity *V* is

$$t_1 = (1 + \frac{V}{C})t \quad (2)$$

The light signal will arrive at Point P2 after the following time:

$$t_2 = t - \frac{r}{C} = t - \frac{V}{C}t = (1 - \frac{V}{C})t$$

in an inertial coordinate system, the time that the light reaches a point at a distance R located against the direction of its motion at a speed V is

$$t_2 = (1 - \frac{V}{C})t \quad (3)$$

Furthermore, we have $t_1 > t_2$.

At $V = 0$, i.e., when K is stationary, the following can be obtained:

$$t_1 = t_2 = t \quad (4)$$

3. Determining the velocity of a body moving uniformly

An observer O and a point light source S are located at the center of an arbitrarily oriented rectangular coordinate system K. System K is located inside an arbitrarily chosen hollow solid body. On both sides of Source S, as shown in Fig. 2, photodetectors are placed along the three axes of the coordinate system at equal distances x = -x = y = -y = z = -z = R. These photodetectors accurately measure the time of arrival of the light front of Source S.

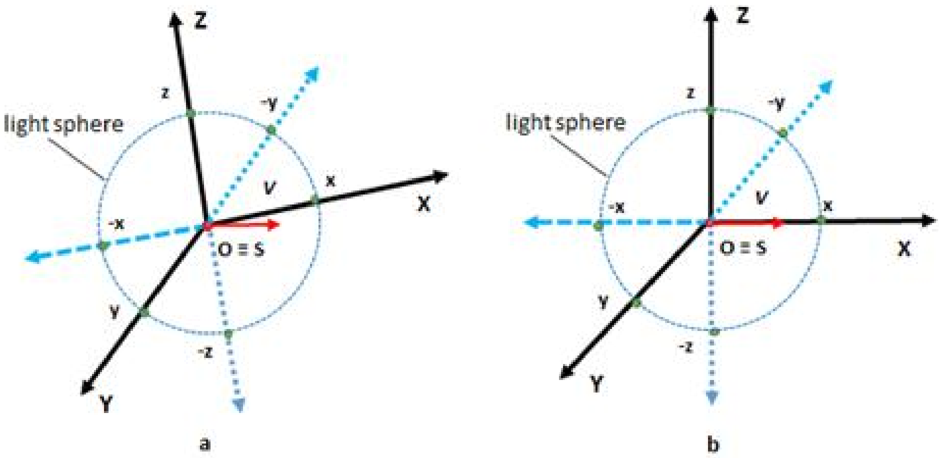

Fig. 2.

a *- Determination of the inertial velocity of a body, moving evenly and in a straight line*

b *- Own inertial coordinate system*

If at time t_0 the observer turns on the light source and measures the arrival times of the light front t_x, t_{-x}, t_y, t_{-y}, t_z, t_{-z} in the photodetectors, then the body is stationary if $t_x = t_{-x} = t_y = t_{-y} = t_z = t_{-z}$. If the times along any axis or simultaneously along all three axes differ, then the body moves. If, for example, on the X-axis the measured times t_x and t_{-x} differ so that $t_x > t_{-x}$, then the direction of the velocity component Vx is positive and vice versa.

By recalling (1) and the considerations above and making substitutions in (2), we can obtain the following:

$$t_x = (1 + \frac{V_x}{C})\frac{R}{C} \tag{5}$$

respectively

$$t_{-x} = (1 - \frac{V_{-x}}{C})\frac{R}{C} \tag{6}$$

If we multiply both sides of Equation (5) by $\frac{C}{R}$ and simplify, then:

$$\frac{V_x}{C} = \frac{C}{R}t_x - 1$$

Therefore, for V_x, we obtain:

$$V_x = C(\frac{C}{R}t_x - 1) \tag{7}$$

Similarly, if we multiply the two sides of Equation (6) by $\frac{C}{R}$, then after the transformations, we obtain:

$$V_{-x} = C(1 - \frac{C}{R}t_{-x}) \tag{8}$$

By applying the same considerations for V_x and V_{-x}, we obtain the velocity components along the Y and Z axes

$$V_Y = C(\frac{C}{R}t_Y - 1) \tag{9}$$

$$V_{-Y} = C(1 - \frac{C}{R}t_{-Y}) \tag{10}$$

$$V_Z = C(\frac{C}{R}t_Z - 1) \tag{11}$$

$$V_{-Z} = C(1 - \frac{C}{R}t_{-Z}) \quad (12$$

If we denote the velocity component along the X axis by $V_{\odot x}$, then we can obtain:

$$V_{\odot x} = V_x, \text{ if } t_x > t_{-x} \tag{13}$$

$$V_{\odot x} = V_{-x}, \text{ if } t_x < t_{-x} \tag{14}$$

$$V_{\odot x} = 0, \text{ if } t_x = t_{-x} \tag{15}$$

Similarly, if we denote the velocity component along the Y-axis by $V_{\odot y}$, then we can obtain:

$$V_{\odot y} = V_y, \text{ if } t_y > t_{-y} \tag{16}$$

$$V_{\odot y} = V_{-y}, \text{ if } t_y < t_{-y} \tag{17}$$

$$V_{\odot y} = 0, \text{ if } t_y = t_{-y} \tag{18}$$

Similarly, if we denote the velocity component along the Z axis by $V_{\odot z}$, then we can obtain:

$$V_{\odot z} = V_z, \text{ if } t_z > t_{-z} \tag{19}$$

$$V_{\odot z} = V_{-z}, \text{ if } t_z < t_{-z} \tag{20}$$

$$V_{\odot z} = 0, \text{ if } t_z = t_{-z} \tag{21}$$

Therefore, the required speed is

$$V = \sqrt{V_{\circledast x}^2 + V_{\circledast \mathrm{y}}^2 + V_{\circledast \mathrm{z}}^2} \tag{22}$$

The velocity *V* is actually the inertial velocity of the body. It is an individual and independent quantity. All bodies that move uniformly and in a straight line have an inertial velocity *V*. It is a vector and its magnitude and direction are individual for each of the bodies. Once we have determined the magnitude and direction of the inertial velocity *V* according to (22), we can conveniently orient the coordinate system so that its positive X-axis coincides with the direction of *V*, as shown in Fig.2b. A coordinate system in which the positive part of the X axis is oriented along the inertial velocity *V* is called a own inertial coordinate system.

A own inertial coordinate system differs from other inertial coordinate systems in that a fixed observer at the origin of the coordinate system knows the magnitude and direction of the inertial velocity *V*.

The own inertial coordinate systems are also infinitely many, as are the inertial coordinate systems. All physical laws in them proceed in the same way as in inertial systems. Since the motion is perpetual, the modulus of inertial velocity satisfies the equation

$$0 < V < C \quad (23)$$

where C is the speed of light in a vacuum.

Any body with inertial velocity V and mass m moves according to Newton's first law of mechanics.

4. Example of an experimental verification

We mounted an opaque, non-flexible pipe with a length of 100 m in a wagon and created a vacuum in it. At one end, we installed a fixed point light source, and at the other end, we installed a photodetector. If the wagon is stationary, then according to (1), when the source is switched on, the light will travel the distance to the photodetector for a time t = $33.356409520 \times 10^{-6}$ s. If the wagon moves uniformly at a speed V = 100 km/h, then in the direction of movement of the wagon, the light will reach the photodetector according to (2) for time $t_1 = 33.356412611 \times 10^{-6}$ s.

Therefore, the difference is $t_1 - t = 3.091 \times 10^{-12}$ s., that is ≅ 3 picoseconds, which is fully measurable with this precise technique[5,7,8].

5. Determining the inertial velocity of another body

Relative velocity between two bodies

When we have n bodies, where n is an arbitrarily chosen large positive integer, then for chosen randomly two bodies i and k with inertial velocities V_i and V_k, the concept of relative speed between them and, or between them and a bystander, arises.

The relative velocity V_R between two inertial moving bodies is by definition a constant because the bodies move inertial[4] . It always lies on the line connecting the centers of mass of the bodies. It only expresses the change of the distance D between them over time. The relative velocity between bodies i and k is:

$$V_R = V_i - V_k \quad (24a),$$

relative to body o_i and

$$V_R = V_k - V_i \quad (24b)$$

relative to body o_k.

From (24a) and (24b) it follows that the relative velocity V_R between any two bodies with inertial velocities of the same magnitude and direction are at relative rest, i.e. $V_R = 0$ regardless of the distance D between them.

Each of the observers O_i and O_κ can measure the instantaneous distance D and the relative velocity V_R between the two bodies oi and O_κ by sending light signals to the other body and measuring with his watch the time for the return of the signal in successive time intervals. The relative velocity according to (24a) and (24b) cannot be assigned to only one body, unlike the inertial velocity, which can completely describe its motion.

Let an observer O_i able to measure distances quite accurately using light signals and precision clocks. If the observer O_i sends a light signal to a body o_k at a time instant τ_0 according to his clock, then the reflected light signal will return to him at a time instant τ_1. Then the instantaneous distance D_1 between the bodies o_i and o_k at time τ_1 is:

$$D1 = \frac{(\tau_1 - \tau_0)C}{2} \qquad (25).$$

If at a later time point τ_2 the observer O_i sends a second light signal to o_k, then the reflected light signal will return to him at a time point τ_3. Then the instantaneous distance D_2 between the bodies o_i and o_k at a time instant τ_3 will be:

$$D2 = \frac{(\tau_3 - \tau_2)C}{2} \qquad (26).$$

Therefore, the observer O_i will determine that the relative velocity V_R between the bodies o_i and o_k is:

$$V_R = \frac{D2-D1}{\tau 3-\tau 1} \qquad (27),$$

where,

if $D_2 < D_1$, then the bodies approach with relative velocity V_R .

if $D_2 > D_1$, then the bodies move apart with relative velocity V_R .

if $D_2 = D_1$, then the bodies are at relative rest relative to each other. The inertial velocities of the two bodies are the same. $V_R = 0$.

Since, by definition, the velocities V_i , V_k and V_R are constants, the observer O_i, having once determined V_R , by (27) can calculate the inertial velocity V_k of a body ok from (24a), given that

$V \equiv V_i$, $V_{\circledast x} \equiv V_{i\circledast x}$, $V_{\circledast y} \equiv V_{i\circledast y}$, $V_{\circledast x} \equiv V_{i\circledast z}$, $V_x \equiv V_{ix}$, $V_{-x} \equiv V_{-ix}$, $V_y \equiv V_{iy}$, $V_{-y} \equiv V_{-iy}$, $V_z \equiv V_{iz}$ и $V_{-z} \equiv V_{-iz}$

Therefore:

$$V_k = \sqrt{V_{i\circledast x}^2 + V_{i\circledast y}^2 + V_{i\circledast z}^2} - \frac{D2-D1}{\tau 3-\tau 1} \qquad (28)$$

Let observer O_k never met observer O_i and can also measure distances accurately using light signals and his precise clocks. If at a time instant Θ_0 according to his clock he sends a light signal to a body o_i, then the reflected light signal will return to him at a time instant Θ_1.

Then the instantaneous distance D'_1 between the bodies o_i and o_k at an instant of time Θ_1 is:

$$D'1 = \frac{(\Theta_1 - \Theta_0)C}{2} \qquad (29).$$

If at a later time instant Θ_2 the observer O_k sends a second light signal to o_i, then the reflected light signal will return to him at a time instant Θ_3. Then the instantaneous distance D'_2 between the bodies oi and ok at an instant of time Θ_3 will be:

$$D'2 = \frac{(\Theta_3 - \Theta_2)C}{2} \qquad (30).$$

Therefore, the relative velocity V_R is:

$$V_R = \frac{D'2-D'1}{\Theta 3-\Theta 1} \qquad (31),$$

where, if $D'_2 < D'_1$, then the bodies approach with a relative velocity V_R .

If $D'_2 > D'_1$, then the bodies move away with a relative velocity V_R .

If $D'_2 = D'_1$, then the bodies are at relative rest relative to each other. The inertial velocities are the same. $V_R = 0$.

Since by definition the velocities V_i , V_k and V_R are constants, then the observer O_k, having once determined V_R , by (31), we can calculate the inertial velocity V_i from (24b) of a body o_i in magnitude and direction, given that

$V \equiv V_k$, $V_{\circledast x} \equiv V_{k\circledast x}$, $V_{\circledast y} \equiv V_{k\circledast y}$, $V_{\circledast x} \equiv V_{k\circledast z}$, $V_x \equiv V_{kx}$, $V_{-x} \equiv V_{-kx}$, $V_y \equiv V_{ky}$, $V_{-y} \equiv V_{-ky}$, $V_z \equiv V_{kz}$ и $V_{-z} \equiv V_{-kz}$

Therefore:

$$V_i = \sqrt{V_{k\circledast x}^2 + V_{k\circledast y}^2 + V_{k\circledast z}^2} - \frac{D'2-D'1}{\Theta 3-\Theta 1} \qquad (32)$$

6. Unity of time

Let us assume, for example, that $V_i > V_k$ and that time in the coordinate system rigidly connected to body o_i flows more slowly than time in the coordinate system rigidly connected to body o_k.

Then we can assume that the time $\Theta = \tau + \delta$, where δ is a positive number and represents the time difference in the two coordinate systems.

If we make substitutions in (29), then

$$D'1 = \frac{(\tau_1 + \delta - \tau_0 - \delta)C}{2} = \frac{(\tau_1 - \tau_0)C}{2} = D1 \qquad (33).$$

If we make analogous substitutions in (30), then

$$D'2 = \frac{(\tau_3 + \delta - \tau_2 - \delta)C}{2} = \frac{(\tau_3 - \tau_2)C}{2} = D2 \qquad (34).$$

Therefore:

$$V_R = \frac{D'2 - D'1}{\theta 3 - \theta 1} = \frac{D2 - D1}{\tau 3 - \tau 1} \qquad (35).$$

From (35) , considering (33) and (34) it follows that

$$\theta 3 - \theta 1 = \tau 3 - \tau 1 \qquad (36)$$

Since $\theta_3 - \theta_1 = \Delta\theta$ is the measurement time in the body-related coordinate system o_k, and

$\tau_3 - \tau_1 = \Delta\tau$ is the measurement time in the body-related coordinate system o_i , it follows that

$\Delta\theta = \Delta\tau$. If we assume the opposite, that the time $\Theta = \tau - \delta$ then after the necessary transformations it is again obtained that $\Delta\theta = \Delta\tau$. The same occurs when $\Theta = \tau$.

That is why the time in the rigidly attached own inertial coordinate systems to the arbitrarily chosen uniformly and rectilinearly moving two bodies o_i and o_k is counted in the same way, regardless of the values and directions of their speeds V_i and V_k.

As we have noticed in the exposition up to here, each of the observers can, with the methodology shown, determine his own movement in space as well as the movement of any other body, using only his own clock and light signals. This does not impose the need to synchronize the watchers' clocks.

7. Conclusion

Determining the inertial velocity of a body does not require the presence of any other body. One simply uses the method by which relation (22) is obtained. Once we have determined our own inertial velocity, we can easily determine our relative velocity to any other body using (27) or (31).

Similarly, the inertial velocity of the other body can be determined by applying (28) and (32). Inertial velocities are independent individual quantities.

Coordinate systems that are rigidly attached to bodies with inertial velocities and oriented in the direction of the speed of movement are called own inertial systems. They are a separate division of inertial systems. In such systems, no procedure for synchronizing the clocks of the observers is necessary, because each of them can determine the movement of the two bodies only with their own clock and their own light signals. When determining the relative speeds of motion, it is not necessary to apply the principle of relativity of Galileo and the Lorentz transformations.

That is why the time measured in the own inertial coordinate systems is counted in the same way in each of them, and therefore the distance between two arbitrarily chosen points of an absolutely rigid body does not depend on the speed of movement.

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