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THEORETICAL CONSIDERATIONS ON SWEEPING PROCESS

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Abstract: *The aim of the paper is to present the simulation of the sweeping process based on a mathematical model that includes the drag force, the lift force, the sideway force, and the gravity. At the beginning, it is presented a short history of the street sweepers, some considerations about the sweeping process and the parameters of the sweeping process. Considering the developed model, in Matlab there is done some simulation for the trajectory of a spherical pebble. The obtained results are presented in graphical shape.*
Keywords: *street sweeper, simulation, Matlab*

1. INTRODUCTION

The street sweepers are vehicles with a particular destination used in streets cleaning in both rural and urban areas and on highways. The street sweepers started to be used in streets cleaning in the same time with the modern development of the cities when the concept of sanitation and waste removal become a necessity. The mechanical street sweeper was invented by Joseph Whitworth in 1843 and was recorded under the name "The Patent Street Sweeping Machine of Manchester" [2], [9]. The main role of the invented equipment was to remove trash from streets to preserve an aesthetic aspect. C.S. Bishop (figures 1 and 2) invented the first American street sweeper in 1849 [14]. Both British and American sweepers were horse-drawn.

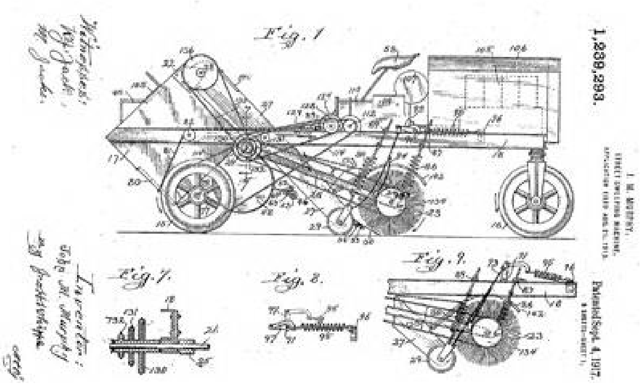

Figure 1: Patent description of street sweeper

Figure 2: Street sweeper

The next step in developing of street sweeper was done in 1917 by John M. Murphy who patented a sweeper (Street Sweeping machine - patent #1,239,293) with a conveyor belt to carry dirt from the broom to the dirt box instead of a slat conveyor [15]. Up to the 1970s, the street trash managing remained the same and there were only small changes until 1990s. The main idea of street sweepers' functionality was to remove large trash. It was found out that the small trash, especially small particles of trash and dust, after the rain, in combination with the storm water, becomes pollutant. Thus, it was developed the idea of manufacturing new generation of street sweeper that have the capacity of clean smaller particles. Nowadays there are new standards and some street sweepers are certified PM10 and have the possibility of cleaning litter smaller than 10 μm [15].
The street sweepers are classified related to the hopper volume in three types: small (up to 1.5 m^3), medium (up to 4.5 m^3, and large (up to 7 m^3). All these street sweepers are equipped with one to three circular brooms and sweeping rolls. The mainly used technology is a dust-free cleaning without water [5]. In this case it is used the

so-called dry-filtered technology that is applied to broom sweepers and regenerative air sweepers. The broom sweepers are considered combined sweepers. In case of conventional broom sweepers with conveyor system, dry-filtered vacuum systems are used. In the sweeping process it is necessary to realize a powerful vacuum and thus it is generated an air stream through the debris hopper, conveyor, and skirted areas. For a long lifetime, a filter is installed between the debris hopper and the vacuum. In this way, the vacuum van is prevented from the dust of the out-put (blown out). Generally, the filters can be mounted outside of the hopper (figure 3) or inside the hopper (figure 4) [5].

Figure 3: Elgin Eagle sweeper system [5]

Figure 4: Tennant sweeper system [5]

A problem of a good functionality is related to the trajectory of the dust that is brushed away by the broom (figure 5). The dust particles and particularly small pebbles are pushed away by the cluster wire bristles, they move on a 3D parabolic trajectory, and the main point is, whether they are moved in the area of nozzle or not (figure 5).

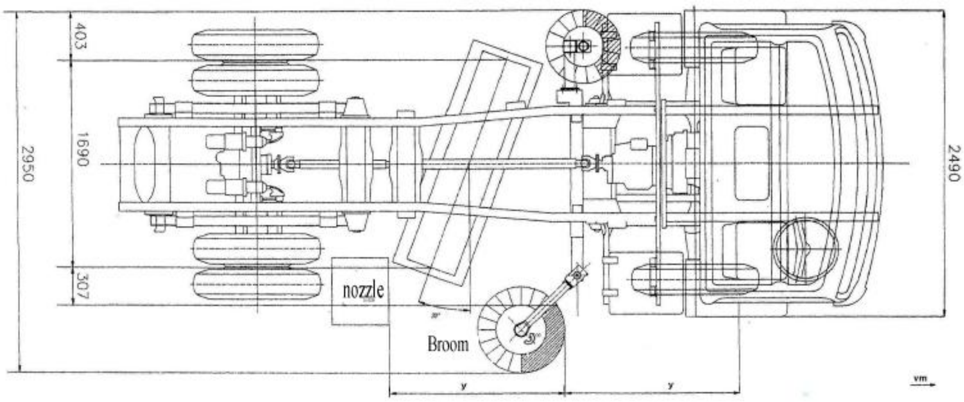

Figure 5: Street sweeper structure

With regard to the importance of the street sweeping, the publications are very limited. In the next sections, a theoretical study of the trajectory of small pebbles is presented.

2. THEORETICAL CONSIDERATIONS

Optimizing the sweeping process is a problem that involves the analyzing of two aspects: the dynamic behaviour of brush and combination of the main parameters describing the sweeping process. The analysis of the dynamics of the broom is already presented in a series of articles. In [11] the dynamics of broom bristles is considered as recessed prismatic bars and subjected to small deformations. A mathematical solution of the cross forces of the brushes is offered. In [12] a research of the brush (broom) is done. A model of an oscillator system is developed being studied the influence on the quality of the sweeping of the brushes. This is discussed in [11] where different sweeping parameters are analyzed with experimental tests. Another topic is studied in [13] where a number of brushes were used for study an oscillating system related to the dynamic behaviour for different particle sizes. Currently the path of a stone is studied, that departs the brush using the combination of key parameters and describing the process of sweeping and simulating the different working conditions. Determination the trajectory is needed in order to find the area where the stone lands on the roadway in relation to the machine. Depending on where the stone lands it can be determined the optimal working parameters: forward speed, speed broom, broom angle of the basket and the basket radius.

The calculation is based on the kinematics model that is shown in Figure 6. The following notations have been made: r is the radius of the circular brooms, H represents the total thickness of the dust, h is the thickness of the broom, $a = H - h$ is the minimum distance between road and broom, ~ represents the angle of the sweep board inclination of the axis Ox, ¨ is the twist angle of the circular brooms (between entrance point A_i and exit point A_e in dust), A_0 is the origin of the frame, x_A is the coordinate in x-direction (time dependent), y_A is the coordinate in y-direction (time dependent), and z_A is the coordinate in z-direction (time dependent), µ represents the angular velocity of the circular brooms, v_m is the speed of the sweeper in travel direction (Oy - axis).

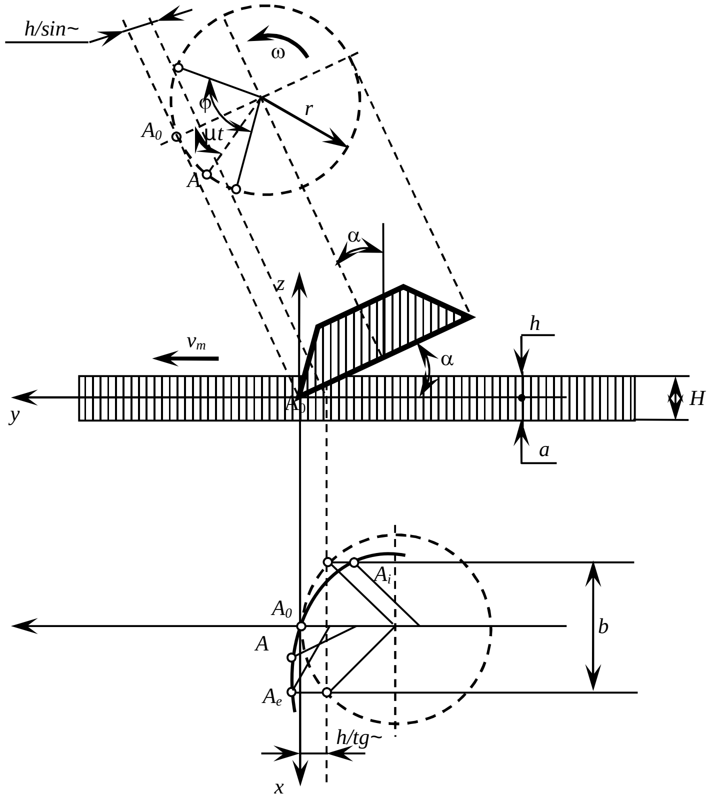

Figure 6: The model of the sweeping process

In the considered model, it is assumed that the pebbles have a spherical shape and are driven by a wire brush, which is considered to be rigid. As a result, the position of the end of a wire brush (i.e. point A) is given by the equations [7]:

$$\begin{cases} x_A = r \cdot \sin(\mu \cdot t); \\ y_A = v_m \cdot t - r \cdot (1 - \cos \mu t) \cdot \cos\text{~}; \\ z_A = r \cdot (1 - \cos \mu \cdot t) \cdot \sin\text{~}, \end{cases} \tag{1}$$

where from can be found the velocities:

$$\begin{cases} \dot{x}_A = \mu \cdot r \cdot \cos \mu \cdot t; \\ \dot{y}_A = v_m - \mu \cdot r \cdot (\sin \mu \cdot t) \cdot \cos\text{~}; \\ \dot{z}_A = \mu \cdot r \cdot (\sin \mu \cdot t) \cdot \sin\text{~}, \end{cases} \tag{2}$$

The presented study is based on both the stone trajectory calculated with the general theory of mechanics and the movement in space using the similarity with balls in sports games. The stone path that follows after the moment of separation from the broom is based on Newton's second law with which both, the gravity and the effects of air brake (drag and lift forces), are taken into account. Considering the movement of the stone in space, the analysis is done on all three directions of a rectangular coordinate system and therefore all three components that arise from the interaction with the air will be considered: the drag force $\vec{F}_D$, the lift force $\vec{F}_L$, and the sideway force $\vec{F}_S$ (figure 7)

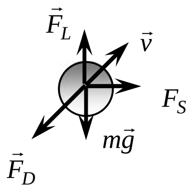

Figure 7: The force system

According Newton’s second law the three forces mentioned above and the gravity are considered [3], [6], [8], and [10]:

$$m\vec{a} = \vec{F}_D + \vec{F}_L + \vec{F}_S + m\vec{g} \qquad (3)$$

where $\vec{a}$ is the acceleration of the pebbles.
The drag force is given by:

$$\vec{F}_D = 0{,}5\,°\,Sv^2 c_D(-\hat{v}) \qquad (4)$$

where $° = 1{,}26\,kg/m^3$ is the air density, S the cross section area of the pebbles, c_D is the dimensionless drag coefficient, $v = |\vec{v}|$ is the pebbles velocity, and $\hat{v} = \vec{v}/v$.
The lift force is perpendicular on the drag force and is given by the equation:

$$\vec{F}_L = 0{,}5\,°\,Sv^2 c_L \hat{n} \qquad (5)$$

where c_L is the lift coefficient, dimensionless, and $\hat{n}$ is the unit vector perpendicular on $\hat{v}$.
The third force, the sideway force $\vec{F}_S$ is:

$$\vec{F}_L = 0{,}5\,°\,Sv^2 c_S(\hat{n}\times\hat{v}) \qquad (6)$$

where c_S is the sideway, dimensionless.
Based on equations (4), (5) and (6), equation (3) can be written as:

$$\vec{a} = «v^2\left[-c_D\hat{v} + c_L\hat{n} + c_S(\hat{n}\times\hat{v})\right] + \vec{g} \qquad (7)$$

where, $« = °A/2m$.
Considering some calculations, the equation (7) can be expressed in all three directions as [4]:

$$\begin{cases} a_x = -«\cdot v\left(c_D v_x + \dfrac{c_L v_x v_z + c_s v v_y}{v_\perp}\right) \\ a_y = -«\cdot v\left(c_D v_y + \dfrac{c_L v_y v_z - c_s v v_x}{v_\perp}\right) \\ a_z = «\cdot v\left(-c_D v_z + c_L v_\perp\right) - g \end{cases} \qquad (8)$$

where, v_x is the velocity on x-axis, v_y is the velocity on y-axis, v_z represents the velocity on z-axis, and $v = \sqrt{v_x^2 + v_y^2 + v_z^2}$, $v_\perp = \sqrt{v_x^2 + v_y^2}$.

The trajectory of the pebble is simulated with a script written in Matlab and a block diagram done in Simulink (figure 8).

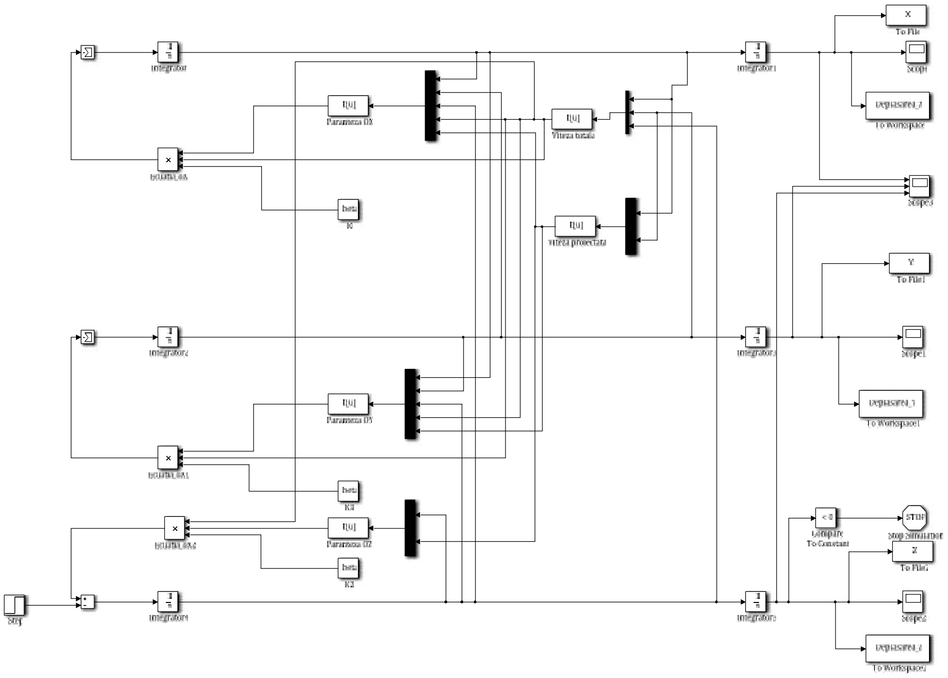

Figure 8: The block diagram used for trajectory simulation

3. RESULTS

The study it based on a pebble (stone) of 10mm diameter. In the model of the trajectory, pebbles with a spherical diameter up to 31 mm and a density of $^\circ{}_p = 1700\, kg/m^3$ are considered.

For each equation ((8) and higher) a branch in the block diagram was considered. As initial moment the depart of the pebble from the dust layer is defined (point A_e). The coordinates x_0, y_0, of the point A_e are calculated; the position z_0 on the z-axis is very small and is considered at zero. The initial values of the velocities are found considering the equation (2). The obtained results are shown in the figures 9 - 12. In the Table 1, the simulations of two data sets are presented.

Table 1: Data used in simulations

Set	Broom rotation (r.p.m)	r radius of the circular brooms [mm]	Radius of the pebble [mm]	Angle $\sim [\circ]$	speed of the sweeper $v_m\, [km/s]$
1	250	300	10	10	6.5
2	200	300	10	10	6.5

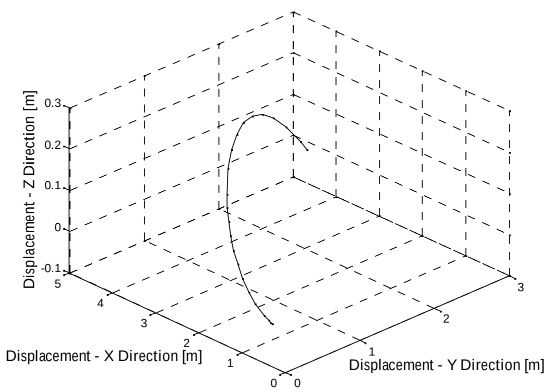

Figure 9: 3D representation for the set 1

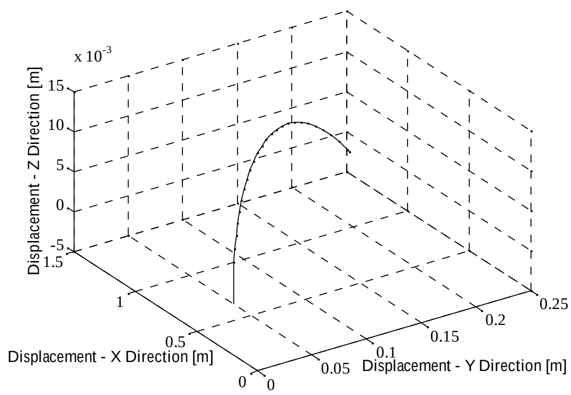

Figure 10: 3D representation for the set 2

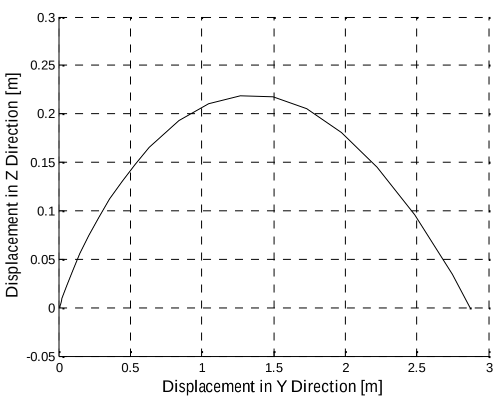

Figure 11: 2D representation for the set 1

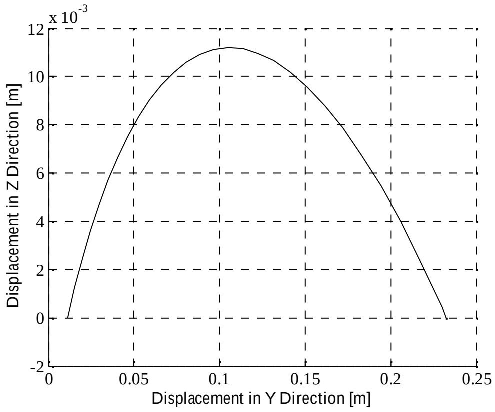

Figure 12: 2D representation for the set 1

5. CONCLUSIONS

The target of the presented paper is the simulation of the trajectory of pebbles during the sweeping process. The simulation is based on a mathematical model defined by equations (8) with data that define de functionality of a street sweeper. Different values of travelled distances of the pebbles are obtained considering initial values of positions and velocities of the pebbles. In the simulation it was assumed, that the vertical component z becomes zero (the moment of the pebbles touchdown). For a better approximation, an experimental set-up has to be realized for investigations related to the precision of the pebbles.

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