

Periodic solutions for a generalized Sitnikov problem with primaries in rigid motion

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Abstract

1 Introduction

In this paper we study the following restricted Newtonian $n + 1$ -body problem P (see figure 1):

- P_1 We have n primary bodies of masses m_1, \dots, m_n and an additional massless particle.
- P_2 The primary bodies are in a homographic motion (see [13, Section 2.9]). This motion is carried out in a plane Π .
- P_3 The massless particle is moving on the perpendicular line to Π passing through the center of masses.

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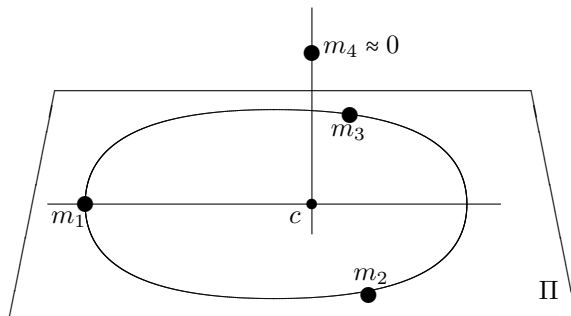


Figure 1: Four-body problem with three primaries

Problems like the one presented have been extensively discussed in the literature. In [27] K. Sitnikov considered the problem of two body in a Keplerian elliptic motion, for small enough eccentricity $e > 0$, and a massless particle moving in the perpendicular line to the orbital plane passing through the center of masses. Sitnikov obtained deep results about existence of solutions with a chaotic behavior (see [19, III(5)]). Periodic solutions for a Sitnikov configuration were considered in [25, 5, 6, 14].

Generalized circular Sitnikov problems ($n \geq 3$) were addressed more recently. In [28] Soulis, Papadakis and Bountis studied existence, linear stability and bifurcations for a problem similar to P . They considered a Lagrangian equilateral triangle configuration for the primaries bodies, which were supposed to have the same mass $m_1 = m_2 = m_3$. In [4] Papadakis and Bountis extend of results of [28] to n primaries ($n \geq 3$) in a polygonal equal mass configuration. Later in [23], Pandey and Ahmad extend the analysis started in [28] to the case when the primaries are oblate (not mass points). In [12] Li, Zhang and Zhao studied a special type of restricted circular $n + 1$ -body problem with equal masses for the primaries in a regular polygon configuration. In the previous papers the primary bodies are in the vertices of a regular polygon. In [16] Marchesin and Vidal studied the problem P for a rigid motion of primaries in a rhomboidal configuration. Periodic solutions for generalized Sitnikov problems with primaries performing no rigid motions were studied in [26, 25]. In [3] Bakker and Simmons studied scape regions for the massless particle in a problem similar to P for a certain type of periodic orbits for primaries.

In the present paper we extend the analysis in....*FALTA*

2 Preliminaries

We start considering n mass points, $n > 2$, of masses m_1, \dots, m_n moving in a Euclidean 3-dimensional space according to Newton's laws of motion. We assume that $x_1(t), \dots, x_n(t)$ are the coordinates (column vectors) of the bodies in some inertial Cartesian coordinate system. We denote by $r_{ij} = |x_i - x_j|$

the Euclidean distance between x_i and x_j . We can suppose, without any loss of generality, that the center of mass $c := \sum_j m_j x_j / M$ ($M := \sum_j m_j$) is fixed at the origin ($c = 0$).

Initially we assume that the bodies are in a *planar homographic motion* on the plane Π (see [13]). That means, assuming that Π is the plane determined by the first two coordinates axes, that

$$x_j(t) = r(t)Q(\theta(t))q_j, \quad (1)$$

where

$$Q(\theta) = \begin{pmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

and $q_j \in \Pi$, $j = 1, \dots, n$ are vectors in a planar *central configuration* (CC) in \mathbb{R}^3 , i.e. there exists $\lambda \in \mathbb{R}$ such that

$$\nabla_j U(q_1, \dots, q_n) + \lambda m_j q_j = 0, \quad j = 1, \dots, n. \quad (2)$$

where the *potential function* U is defined by:

$$U(x) = \sum_{i < j} \frac{m_i m_j}{r_{ij}}, \quad (3)$$

and ∇_j denotes the 3-dimensional partial gradient with respect to x_j . For simplicity we denote $q := (q_1, \dots, q_n)$.

According to [13, Eq. (2.16)] the functions $r(t)$ and $\theta(t)$ solves the two-dimensional Kepler problems in polar coordinates, i.e.

$$\begin{aligned} \ddot{r}(t) - r(t)\dot{\theta}(t)^2 &= -\frac{\lambda}{r(t)^2} \\ r(t)\ddot{\theta}(t) + 2\dot{r}(t)\dot{\theta}(t) &= 0. \end{aligned} \quad (4)$$

In the particular case of *rigid motion*, we have $r(t) \equiv 1$ and $\theta(t) = \sqrt{\lambda}t + \theta(0)$. Therefore the primaries bodies perform a periodic motion with period $T := 2\pi/\nu$, where $\nu^2 = \lambda$.

Let $x_0(t)$ denotes the position of the massless particle. According to the Newtonian equations of motion q satisfies

$$\ddot{x}_0 = \sum_{i=1}^n \frac{m_i(x_i - x_0)}{|x_i - x_0|^3} =: f(t, x_0). \quad (5)$$

3 Admissible configurations

Henceforth we denote by L the coordinate z axis. It is well known that a necessary and sufficient condition for that L be invariant under the flow associated to the non autonomous system (5), is that $f(t, L) \subset L$ for all t , i.e. L is *f-invariant* for every t .

Definition 3.1. We say that a central configuration q is admissible if and only if it satisfies that for any $r > 0$, such that the set

$$F_r := \{i : |q_i| = r\}$$

is non empty, then

$$\sum_{i \in F_r} m_i q_i = 0. \quad (6)$$

i.e. every maximal set of bodies which are equidistant from origin has center of mass equal to 0.

Theorem 3.2. L is f -invariant for every t if and only q is admissible.

For the proof of the previous theorem we need the following result

Lemma 3.3. For $c > 0$ we define the function $y_c(t) := (c + t)^{-3/2}$. If $0 < t_1 < t_2 < \dots < t_k$ then the functions $y_j(t) := y_{t_j}(t)$ are linearly independent on each open interval $\mathcal{I} \subset \mathbb{R}^+$.

Proof. It is sufficient to prove that Wronskian

$$W := W(y_1, \dots, y_k)(t) = \det \begin{pmatrix} y_1 & \dots & y_k \\ \frac{dy_1}{dt} & \dots & \frac{dy_k}{dt} \\ \vdots & \ddots & \vdots \\ \frac{d^{k-1}y_1}{dt^{k-1}} & \dots & \frac{d^{k-1}y_k}{dt^{k-1}} \end{pmatrix}$$

is not null on \mathcal{I} .

Using induction is easy to show that

$$\frac{d^i y_c}{dt^i} = \beta_i y_c^{\frac{2i+3}{3}}, \quad \text{for some } \beta_i \neq 0, \text{ and for all } i = 1, \dots \quad (7)$$

Fix any $t \in I$. Then, according to (7) and writing $\lambda_j := (t + t_j)^{-1}$, we have

$$\begin{aligned} W(t) &= \det \begin{pmatrix} \lambda_1^{3/2} & \lambda_2^{3/2} & \dots & \lambda_k^{3/2} \\ \beta_1 \lambda_1^{5/2} & \beta_1 \lambda_2^{5/2} & \dots & \beta_1 \lambda_k^{5/2} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{k-1} \lambda_1^{k+1/2} & \beta_{k-1} \lambda_2^{k+1/2} & \dots & \beta_{k-1} \lambda_k^{k+1/2} \end{pmatrix} \\ &= \beta_1 \beta_2 \dots \beta_{k-1} \lambda_1^{3/2} \lambda_2^{3/2} \dots \lambda_k^{3/2} \det \begin{pmatrix} 1 & 1 & \dots & 1 \\ \lambda_1 & \lambda_2 & \dots & \lambda_k \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_1^{k-1} & \lambda_2^{k-1} & \dots & \lambda_k^{k-1} \end{pmatrix} \\ &= \beta_1 \beta_2 \dots \beta_{k-1} \lambda_1^{3/2} \lambda_2^{3/2} \dots \lambda_k^{3/2} \prod_{1 \leq i < j \leq n} (\lambda_j - \lambda_i), \end{aligned}$$

where the last equality follows of the well known Vandermonde determinant identity. Therefore $W \neq 0$ if and only if $\lambda_i \neq \lambda_j$, $i \neq j$, which in turn is equivalent to $t_i \neq t_j$, $i \neq j$. \square

Proof of Theorem 3.2. The condition $f(t, L) \subset L$ for all t is equivalent to

$$\sum_{i=1}^n \frac{m_i r(t) Q(\theta(t)) q_i}{(r(t)^2 |q_i|^2 + z^2)^{3/2}} = 0, \quad (8)$$

for every $t, z \in \mathbb{R}$.

Let $D = \{|q_i| : i = 1, \dots, n\}$. Suppose that $D = \{s_1, \dots, s_k\}$, with $s_i \neq s_j$ for $i \neq j$, and $\{1, \dots, n\} = F_1 \cup \dots \cup F_k$, where if $i \in F_j$ then $|q_i| = s_j$. Then, multiplying equation (8) by $r(t)^2 Q^{-1}(\theta(t))$ and writing $\zeta = (z/r(t))^2$ we have that (8) is equivalent to

$$\sum_{j=1}^k \left\{ \frac{1}{(s_j^2 + \zeta)^{3/2}} \sum_{i \in F_j} m_i q_i \right\} = 0.$$

According to Lemma 3.3, the last equation is equivalent to (6). \square

4 Admissible collisionless configurations for $n \leq 4$

In this section we find all admissible collisionless configuration with $n \leq 4$. We observe that the collisionless condition for a configuration q_1, \dots, q_n implies that $q_i \neq 0$ for $i = 1, \dots, n$. From the fact that the center of masses is an excluded position we obtain

$$F_r \neq \emptyset \Rightarrow \#F_r \geq 2. \quad (9)$$

Trivially, a configuration of two point masses m_1 and m_2 is admissible if and only if $m_1 = m_2$.

If $n = 3$, from (9), the configuration consists of three equidistant bodies from the origin. Therefore, it must to be the Lagrangian equilateral triangle configuration. Now, by equation (6) and an elementary geometrical reasoning we have that $m_1 = m_2 = m_3$.

The case $n = 4$ is more interesting. We will use the following result which can be seen in [18].

“Let q be a planar configuration. For each pair, i, j , the line containing q_i and q_j together with its perpendicular bisector form axes which divide the plane into four quadrants. The union of the first and third quadrants is an hourglass shaped region which will be called a ‘cone’; similarly, the second and fourth quadrants together form another cone. The phrase ‘open cone’ refers to a cone minus the axes.”

Theorem 4.1 (Perpendicular Bisector Theorem). *Let q be a planar central configuration and let q_i and q_j be any two of its points. Then if one of the two open cones determined by the line through q_i and q_j and its perpendicular bisector contains points of the configuration, so does the other one.*

Next we characterize all the 4-body admissible collisionless configurations.

Theorem 4.2. *Let q be a 4-body central configuration. Then q is admissible and collisionless if and only if, for a suitable enumeration of bodies, $q_1 = -q_3$, $q_2 = -q_4$, $m_1 = m_3$, $m_2 = m_4$, and q is of some of the following mutually exclusive types:*

CCcl. *collinear,*

CCr. *a rhombus with $r_{13} < r_{24}$ and $m_1 > m_2$,*

CCs. *a square with four equal masses.*

Proof. Since (9) we have two cases.

Case 1. $m_1 \geq m_2$, $|q_1| \neq |q_2|$, $|q_1| = |q_3|$ and $|q_2| = |q_4|$. Now (6) implies that $m_1 = m_3$, $m_2 = m_4$, $q_1 = -q_3$ and $q_2 = -q_4$. We divide the plane in two cones C_i , $i = 1, 2$, by means of the line P joining q_1 and q_3 together with its perpendicular bisector M . From Theorem 4.1, if q_2 is in C_1 , then q_4 is in C_2 , and vice versa. This is a contradiction with the fact that $q_2 = -q_4$. Then $q_2, q_4 \in P$ or $q_2, q_4 \in M$, i.e. q is collinear or is a rhombus with equal masses in opposite vertices. In the first case, q is of CCcl type. In the second case, if $m_1 > m_2$, was proved in [15, Eqs. (3.44) and (3.45)] that $r_{13} < r_{24}$, hence q is of CCr type. From [24, Corollary 2] if $m_1 = m_2$ then the configuration is a square witch is a contradiction with the fact that $|q_1| \neq |q_2|$.

Case 2. $|q_1| = |q_2| = |q_3| = |q_4|$. In this situation, was proved in [9] that the configuration is the equal mass square. \square

5 Massless particle motion

In this section we analyze all possible motions for the massless particle x_0 . In particular we will see that all motion is periodic or is a scape trayectory. We will find that there exists T_0 -periodic solutions for all T_0 in an interval $(\sigma(q), +\infty)$. This fact implies that there exists an infinity quantity of periodic solutions for the entire $n + 1$ -body system.

In this and next sections we suppose that the primaries bodies are in a T -periodic rigid motion asociate to an admissible collisionless q , i.e $r(t) \equiv 1$ and from the remark follows (4), $\theta(t) = \sqrt{\lambda}t$. Without loss of generality, we have assumed that $\theta(0) = 0$. For the particle, we assume that it is moving on L . Therefore, we assume that $x_0(t) = (0, 0, z(t))$. According to Theorem 3.2, x_0 is solution of (5), if and only if $z(t)$ is solution of the autonomous equation

$$\ddot{z} = - \sum_{i=1}^n \frac{m_i z}{(s_i^2 + z^2)^{3/2}}, \quad (10)$$

where $s_i = |q_i|$.

The second order equation (10) is consevative, therefore solutions conserve the energy

$$E(z, v) := \frac{|v|^2}{2} - \sum_{i=1}^n \frac{m_i}{(s_i^2 + z^2)^{\frac{1}{2}}}, \quad (11)$$

i.e. $E(z(t), \dot{z}(t))$ is constant.

Following [16] we introduce the next concepts.

Definition 5.1. A solution $z(t)$ of (10) such that $\lim_{t \rightarrow \infty} z(t) = \infty$ is called *hyperbolic* for $t \rightarrow \infty$ when $\lim_{t \rightarrow \infty} \dot{z}(t) = z_\infty \neq 0$ and is called *parabolic* if $\lim_{t \rightarrow \infty} \dot{z}(t) = 0$.

The following theorem characterize all the possible motions for the massless particle.

Theorem 5.2. We assume that q is a admissible collisionless configuration and the primaries are in a rigid motion. Every solution of (10) is of the some following types:

1. Hyperbolic, when $E > 0$,
2. Parabolic, when $E = 0$,
3. Periodic, when $E_{min} := -\sum_{i=1}^n \frac{m_i}{s_i} < E < 0$.
4. Equilibrium solution when $E = E_{min}$.

Proof. We follow a standard argument for hamiltonian systems (see [?]).

We plot the level sets of $S(E) = \{(z, v) : E(z, v) = E\}$, in the phase space (z, v) , for different values of E . An elementary analysis shows that

- If $E \geq 0$ then $S(E)$ is the union of two bounded graphs. They are symmetric with respect to z -axis, each of which is contained in some semiplane $v > 0$ or $v < 0$. The v -positive branch is the graph of a function $v(E, z)$, which is decreasing with respect to $|z|$. Moreover, $\lim_{|z| \rightarrow \infty} v(E, z) = \sqrt{2E}$.
- For every $E \geq E_{min}$, the energy curve cut the v -axis at $\pm(2E + 2\sum_{i=1}^n m_i s_i^{-1})^{\frac{1}{2}}$.
- If $E_{min} < E < 0$ then $S(E)$ is a simple closed curve symmetric with respect to z and v axes.
- An energy curve cut the z -axis, only in the case that $E < 0$, at $\pm z_E$, where z_E is the only positive solution of $-\sum_{i=1}^n m_i (s_i^2 + z_E^2)^{-\frac{1}{2}} = E$.

In the figure 1 we show the phase portrait for two equal masses primaries.

The function $\varphi(t) = (z(t), \dot{z}(t))$ solves the system $\dot{\varphi}(t) = F(\varphi(t))$, where $F(z, v) = (v, -\sum_{i=1}^n m_i z (s_i^2 + z^2)^{-3/2})$. The only stationary point of F is $(z, v) = (0, 0)$. Therefore, the level surfaces $S(E)$, with $E \neq E_{min}$, not contains stationary points. A well know argument implies that the trayectories $t \mapsto (z(t), \dot{z}(t))$ fill completely the energy curves.

We note that if $E \geq 0$ and $v(E, 0) > 0$ ($v(E, 0) < 0$) then $z(t)$ is increasing (decreasing) with respect to t . For all the above if $E \geq 0$ then $|z(t)| \rightarrow \infty$ when $t \rightarrow \infty$. Moreover $\lim_{t \rightarrow \infty} \dot{z}(t) = \pm\sqrt{2E}$. From this we conclude that the trayectories is hyperbolic when $E > 0$ and it is parabolic in the case $E = 0$.

In the case that $E_{min} < E < 0$ we have that the trayectories is contained in a closed curve, therefore it is periodic orbit.

Finally if $E = E_{min}$ clearly we have that $z(t) \equiv 0$. □

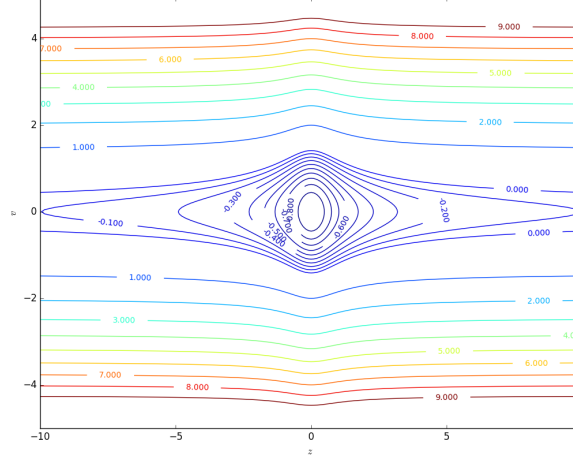


Figure 2: Energy level for two equal mass primaries

Theorem 5.3. *We denote by $T_0(E)$ the minimal period for a solution of (10) with $E_{min} < E < 0$. Then*

1. *for z_E the only positive solution of $-\sum_{i=1}^n m_i(s_i^2 + z_E^2)^{-\frac{1}{2}} = E$*

$$T_0(E) = 2^{3/2} \int_0^{z_E} \left(E + \sum_{i=1}^n m_i(s_i^2 + z^2)^{-\frac{1}{2}} \right)^{-\frac{1}{2}} dz, \quad (12)$$

2. *$T_0(E)$ is an increasing function.*

3. *$T_0((E_{min}, 0)) = (T_{min}, +\infty)$, where $T_{min} = 2\pi \left(\sum_{i=1}^n \frac{m_i}{s_i^3} \right)^{-1/2}$.*

Proof. Let $E_{min} < E < 0$ and let $z(t)$ be a solution with $z(0) = 0$ and $\dot{z}(0) = \sqrt{2(E - E_{min})}$. Then $E(z(0), \dot{z}(0)) = E$. Therefore $z(t)$ is $T_0(E)$ -periodic. As a consequence of the symmetries of the equation we have that $z(T_0(E)/4) = z_E$. Then, taking account (11) we have that

$$\begin{aligned} \frac{T_0}{4} &= \int_0^{T_0/4} \left(E + \sum_{i=1}^n m_i(s_i^2 + z^2)^{-\frac{1}{2}} \right)^{-\frac{1}{2}} z'(t) dt \\ &= \frac{1}{\sqrt{2}} \int_0^{z_E} \left(E + \sum_{i=1}^n m_i(s_i^2 + z^2)^{-\frac{1}{2}} \right)^{-\frac{1}{2}} dz, \end{aligned}$$

and we have proved item 1. In order to prove item 2 we note that

$$\begin{aligned} 2^{-3/2}T_0(E) &= \int_0^{z_E} \left(\sum_{i=1}^n m_i \left((s_i^2 + z^2)^{-\frac{1}{2}} - (s_i^2 + z_E^2)^{-\frac{1}{2}} \right) \right)^{-\frac{1}{2}} dz \\ &= \int_0^{z_E} (z_E^2 - z^2)^{-\frac{1}{2}} f(z, z_E) dz \\ &= \int_0^1 (1 - u^2)^{-\frac{1}{2}} f(z_E u, z_E) du, \end{aligned}$$

where

$$f(z, z_E) = \left(\sum_{i=1}^n m_i \{ (s_i^2 + z^2)(s_i^2 + z_E^2) \}^{-\frac{1}{2}} \{ (s_i^2 + z^2)^{\frac{1}{2}} + (s_i^2 + z_E^2)^{\frac{1}{2}} \}^{-1} \right)^{-\frac{1}{2}}.$$

We note that $f(z_E u, z_E)$ is a increasing function with respect to z_E for $u \in [0, 1]$ fix. This implies item 2.

On the other hand

$$\lim_{z_E \rightarrow 0} f(z_E u, z_E) = \left(\sum_{i=1}^n \frac{m_i}{2s_i^3} \right)^{-\frac{1}{2}} \quad \text{and} \quad \lim_{z_E \rightarrow \infty} f(z_E u, z_E) = \infty.$$

Therefore, from the dominated convergence theorem and monotone convergence theorem we have that

$$\lim_{z_E \rightarrow 0} T_0 = 2\pi \left(\sum_{i=1}^n \frac{m_i}{s_i^3} \right)^{-\frac{1}{2}} \quad \text{and} \quad \lim_{z_E \rightarrow \infty} T_0 = \infty.$$

Finally, since $T_0 = T_0(z_E)$ is continuous and increasing respect to z_E we conclude the affirmation in the item 3. \square

Remark 1. It is possible to use the classical theory of hamiltonian systems (see [2]) to derive the formula (12) (see [1] for a related problem).

Remark 2. Let us to show a second proof of item 3 of Theorem 5.3.

The inequality $T_0 > T_{min}$ is consequence of comparison Sturm's theorem applied to equations $z'' + q_1(z)z = 0$, where $q_1(z) = \sum_{i=1}^n m_i (s_i^2 + z^2)^{-3/2}$, and $z'' + (\sum_{i=1}^n m_i s_i^{-3})z = 0$. This prove that $T_0((E_{min}, 0)) \subset (T_{min}, +\infty)$.

For the reverse inclusion we follow arguments of [30] and [12], based on variational principles.

Let $T_0 > T_{min}$. We consider the action integral

$$\mathcal{I}(z) = \int_0^{T_0} \frac{1}{2} |z'|^2 + \sum_{i=1}^n \frac{m_i}{\sqrt{s_i^2 + z^2}} dt,$$

Then T_0 -periodic solutions of (10) are critical points of \mathcal{I} in the space $H^1(\mathbb{T}, \mathbb{R})$, where $\mathbb{T} = \mathbb{R}/T_0\mathbb{Z}$, of the functions absolutely continuous, T_0 -periodic with $z' \in L^2(\mathbb{T}, \mathbb{R})$ (see [17, Cor. 1.1]). We prove the existence of critical points by

means of the direct method of calculus of variations, i.e. we will prove that \mathcal{I} has minimum. The functional \mathcal{I} is not coercive in $H^1(\mathbb{T}, \mathbb{R})$, this deficiency is drawn with symmetry techniques (see [29]). The group \mathbb{Z}_2 acts on $H^1(\mathbb{T}, \mathbb{R})$ according to the following assignments $(0 \cdot z)(t) = z(t)$ and $(1 \cdot z)(t) = -z(t + \frac{T_0}{2})$. The functional \mathcal{I} is \mathbb{Z}_2 -invariant, i.e. $\mathcal{I}(g \cdot z) = \mathcal{I}(z)$. We define the space of all \mathbb{Z}_2 -symmetric (this symmetry is called the Italian symmetry) functions

$$\Lambda(\mathbb{T}, \mathbb{R}) := \{z \in H^1(\mathbb{T}, \mathbb{R}) \mid \forall g \in \mathbb{Z}_2 : z = g \cdot z\}.$$

The functional \mathcal{I} restricted to Λ is coercive. This fact follows from an obvious adaptation of proposition 4.1 of [29]. We note that $F(z) := \sum_{i=1}^n m_i (s_i^2 + z^2)^{-\frac{1}{2}}$ satisfies the condition (A) in [17, p. 12], then \mathcal{I} is continuously differentiable and weakly lower semicontinuous on $H^1(\mathbb{T}, \mathbb{R})$ (see [17, p. 13]). Therefore \mathcal{I} has a minimum z_0 in $\Lambda(\mathbb{T}, \mathbb{R})$. Then by the Palais' principle symmetric criticality, z_0 is a critical point of \mathcal{I} in $H^1(\mathbb{T}, \mathbb{R})$ (see [29] and [22]).

We use the second variation $\delta^2 \mathcal{I}$ in order to show that $z_0 \not\equiv 0$. It is well known (see [10, Th. 1.3.1]) that if z_0 is a minimum of \mathcal{I} on $H^1(\mathbb{T}, \mathbb{R})$ then $\delta^2 \mathcal{I}(z_0, \varphi) \geq 0$ for all $\varphi \in H^1(\mathbb{T}, \mathbb{R})$. In our case

$$\delta^2 \mathcal{I}(0, \varphi) = \int_0^{T_0} |\varphi'|^2 - \sum_{i=1}^n \frac{m_i}{s_i^3} \varphi^2 dt,$$

(see [10, Eq. 1.3.6]). In particular for $\varphi(t) = \sin(2\pi t/T_0)$ it follows from $T_0 > T_{min}$ that

$$\delta^2 \mathcal{I}(0, \varphi) = \left(\frac{4\pi^2}{T_0^2} - \sum_{i=1}^n \frac{m_i}{s_i^3} \right) \frac{T_0}{2} < 0. \quad (13)$$

It is sufficient to guarantee that $z_0 \equiv 0$ is not a minimum.

This second proof, unlike the first one, does not guarantee that T_0 is the minimum period for z_0 . It could happen that z_0 had period T_0/m , with natural $m \in \mathbb{N}$. Because of Italian symmetry this m should be odd.

Corollary 5.4. *The complete $n + 1$ -body has a infinity quantity of periodic solutions.*

Proof. Let l/m be a rational number with $lT/m > T_{min}$. Then, there exists a solution of the entire system with period lT . \square

6 Synchronous solutions and pyramidal CC

If the equation (10) has a T -periodic solution, we say that the solution is *synchronous*. In [12] was studied the existence of synchronous solutions for n equal mass primary bodies in a regular polygon configuration.

In this section we establish a relation between the existence of synchronous solutions and the concept of pyramidal central configuration (see [7, 8, 21]).

Definition 6.1. *A central configuration of $n + 1$ mass point q_1, \dots, q_{n+1} in \mathbb{R}^3 is called a pyramidal central configuration (PCC) if and only if n points, we say q_1, \dots, q_n , are in some plane Π and q_{n+1} is not.*

The following lemma was proved in [21] (see also [8])

Lemma 6.2 ([21], Lemma 2.1). *Let q_0, \dots, q_n be a PCC such that m_0 is off the plane containing m_1, \dots, m_n . If $m_0 > 0$ then m_0 is equidistant from m_1, \dots, m_n .*

We remark that the condition $m_0 > 0$ is important in the previous Lemma. We will show below examples of two PCC with $m_0 = 0$ which do not satisfy the conclusion of Lemma 6.2.

Proposition 6.3. *We assume that $q = q_1, \dots, q_n$ is an admissible collisionless configuration and that the primaries are in a rigid motion. Then, there is a synchronous solution if and only if there exists $c \in \mathbb{R}$ such that the points q_0, \dots, q_n associated to the masses m_0, \dots, m_n , with $q_0 = (0, 0, c)$ and $m_0 = 0$, form a PCC.*

Proof. We start assuming that there exist a synchronous solution. As a consequence of the Theorem 5.3(3) and the fact that $T^2 = 4\pi^2/\lambda$ we have that

$$\lambda < \sum_{i=1}^n \frac{m_i}{s_i^3}. \quad (14)$$

Since $\sum_{i=1}^n m_i (s_i^2 + c^2)^{-3/2} \rightarrow 0$, when $c \rightarrow +\infty$, there exists $c \in \mathbb{R}$ such that $\sum_{i=1}^n m_i (s_i^2 + c^2)^{-3/2} = \lambda$. Therefore

$$-\sum_{i=1}^n \frac{m_i c}{(s_i^2 + c^2)^{3/2}} = -\lambda c. \quad (15)$$

As q_1, \dots, q_n is an admissible configuration then

$$\sum_{i=1}^n \frac{m_i q_i}{(s_i^2 + c^2)^{3/2}} = (0, 0). \quad (16)$$

We define $q_{n+1} := (0, 0, c)$ and $m_{n+1} = 0$. The equations (15), (16) and the facts that q_1, \dots, q_n is a CC, with constant λ , implies that q_1, \dots, q_{n+1} and m_1, \dots, m_{n+1} form a PCC.

The proof of the reciprocal statement follows in a direct way. \square

Corollary 6.4. *We assume that $q = q_1, \dots, q_n$ is an admissible collisionless configuration and that the primaries are in a rigid motion. Then, there is a synchronous solution if and only if*

$$\sum_{i < j} \frac{m_i m_j}{r_{ij}} < \left(\sum_{i=1}^n \frac{m_i}{s_i^3} \right) \left(\sum_{i=1}^n m_i s_i^2 \right). \quad (17)$$

Proof. The result is consequence of (14) and the fact that $T^2 = 4\pi^2 \sum_{i=1}^n m_i |q_i|^2 / U$ (see [13, p. 109]). \square

The sufficiency of the condition $n \leq 472$ in the following corollary was proved in [12].

Corollary 6.5. *We suppose that q is the equal masses regular polygon configuration (this is an admissible CC). Then there exists a synchronous solution if and only if $2 \leq n \leq 472$.*

Proof. In this case $s_1 = s_2 = \dots = s_n =: r$ and $m_1 = m_2 = \dots = m_n =: m$. Then, from the law of cosines we obtain

$$\sum_{i < j} \frac{m_i m_j}{r_{ij}} = \frac{nm^2}{4r} \sum_{j=1}^{n-1} \frac{1}{\sin\left(\frac{j\pi}{n}\right)}.$$

Therefore the condition (17) is equivalent to

$$\frac{1}{n} \sum_{j=1}^{n-1} \frac{1}{\sin\left(\frac{j\pi}{n}\right)} < 4. \quad (18)$$

This inequality was also derived by Li, J. et al. in [12], where the authors proved (performing computer calculations) that inequality (18) holds true for $2 \leq n \leq 472$. Let us prove that any other n does not satisfies (18).

Using that $1/\sin(x)$ is a convex function on $[0, \pi]$ and the composite trapezoid rule (see [11]) we have that

$$\begin{aligned} \int_{\frac{\pi}{n}}^{\frac{n-1}{n}\pi} \frac{1}{\sin(x)} dx &\leq \frac{\pi}{2n} \left\{ \frac{1}{\sin\left(\frac{\pi}{n}\right)} + \frac{1}{\sin\left(\frac{n-1}{n}\pi\right)} + 2 \sum_{j=2}^{n-2} \frac{1}{\sin\left(j\frac{\pi}{n}\right)} \right\} \\ &= \frac{\pi}{n} \sum_{j=1}^{n-2} \frac{1}{\sin\left(j\frac{\pi}{n}\right)}. \end{aligned}$$

Therefore

$$\begin{aligned} \frac{1}{n} \sum_{j=1}^{n-1} \frac{1}{\sin\left(\frac{j\pi}{n}\right)} &\geq \frac{1}{\pi} \int_{\frac{\pi}{n}}^{\frac{\pi(n-1)}{n}} \frac{1}{\sin(x)} dx + \frac{1}{n \sin\left(\frac{n-1}{n}\pi\right)} \\ &= \frac{1}{2\pi} \log \left(\frac{1 - \cos(x)}{1 + \cos(x)} \right) \Big|_{\frac{\pi}{n}}^{\frac{n-1}{n}\pi} + \frac{1}{n \sin\left(\frac{\pi}{n}\right)} \\ &= \frac{1}{\pi} \left\{ \log \left(\frac{1 + \cos\left(\frac{\pi}{n}\right)}{1 - \cos\left(\frac{\pi}{n}\right)} \right) + \frac{\pi/n}{\sin\left(\frac{\pi}{n}\right)} \right\} \\ &=: f\left(\frac{\pi}{n}\right). \end{aligned}$$

It is easy to see that $f(x)$ is a decreasing function on $(0, \pi/2)$. Moreover $f(\pi/842) \approx 4.0006 > 4$. Therefore, if $n \geq 842$ then n does not satisfies inequality (18). The validity of the inequality (18), for $n \leq 841$, is easily checked using computer. This gives the result that the inequality holds for all $n \leq 472$. \square

Our next objective is to verify that condition (17) is satisfied for all admissible CC of 3-body or 4-body. Since we have already proved, in Corollary 6.5, that (17) holds for a equilateral triangle and square configurations of equal masses bodies, it only rest to prove, in virtue of Theorem 4.2, the following result.

Theorem 6.6. *The central configurations CCcl and CCr satisfy condition (17).*

Proof. Let's start by analyzing the central configuration CCr. We can suppose without loss of generality that $q_1 = -q_3 = (0, y)$ for $y > 0$, $q_2 = -q_4 = (1, 0)$. Recall that $y < 1$. The condition (17) becomes

$$\frac{m_1^2}{2y} + \frac{4m_1m_2}{\sqrt{1+y^2}} + \frac{m_2^2}{2} < \left(\frac{2m_1}{y^3} + 2m_2 \right) (2m_1y^2 + 2m_2).$$

As $m_1^2/(2y) < 4m_1^2/y$, $m_2^2/2 < 4m_2^2$ and $4m_1m_2/\sqrt{1+y^2} < 4m_1m_2/y^3$ (since $y < 1$), we have that the inequality holds.

Now we consider the central configuration CCl. We can suppose without loss of generality that $q_1 = -q_3 = 1$, $q_2 = -q_4 = x$ with $0 < x < 1$, and $m_1 = m_3 = \mu$, $m_2 = m_4 = 1 - \mu$, with $0 < \mu < 1$. Then the inequality (17) becomes

$$\frac{2\mu(1-\mu)}{1-x} + \frac{2\mu(1-\mu)}{1+x} + \frac{\mu^2}{2} + \frac{(1-\mu)^2}{2x} < 4\mu^2 + 4\mu(1-\mu)x^2 + \frac{4\mu(1-\mu)}{x^3} + \frac{4(1-\mu)^2}{x}.$$

As $\mu^2/2 < 4\mu^2$ and $(1-\mu)^2/(2x) < 4(1-\mu)^2/x$ (without taking into account the term $4\mu(1-\mu)x^2$) we just have to show that

$$\frac{2\mu(1-\mu)}{1-x} + \frac{2\mu(1-\mu)}{1+x} < \frac{4\mu(1-\mu)}{x^3},$$

and this is equivalent to see that

$$\frac{x^3}{1-x^2} < 1. \quad (19)$$

The values of x involved in the above inequality are such that the configuration for the vector mass $(\mu, 1-\mu, 1-\mu, \mu)$ is central, by Moulton [20], fixed a mass μ there is only one value x satisfying this condition. So, we can define $x(\mu)$ as such value of x . We note that $x^3/(1-x^2)$ is an increasing function with respect to $x \in (0, 1)$ and it is less than 1 for $x \in (0, 3/4)$. Hence, if we could prove that $x(\mu)$ is a decreasing function and

$$\lim_{\mu \rightarrow 0} x(\mu) < 3/4 \quad (20)$$

we would have justified (19).

Let's first prove that $x(\mu)$ is a decreasing function. Replacing q_j^0 , m_j and eliminating λ from the equations (2) we get

$$\frac{\mu}{4} - \frac{\mu}{x(x+1)^2} + \frac{\mu}{x(-x+1)^2} + \frac{-\mu+1}{(x+1)^2} + \frac{-\mu+1}{(-x+1)^2} - \frac{1}{x^3} \left(-\frac{\mu}{4} + \frac{1}{4} \right) = 0$$

which is equivalent to

$$\mu = -\frac{8x^5 - x^4 + 8x^3 + 2x^2 - 1}{(x-1)(x+1)(x^5 - 9x^3 + x^2 - 1)}.$$

Therefore

$$\frac{d\mu}{dx} = \frac{x^2 (16x^9 - 3x^8 + 32x^7 + 12x^6 - 304x^5 - 2x^4 + 44x^2 - 51)}{(x-1)^2 (x+1)^2 (x^5 - 9x^3 + x^2 - 1)^2}.$$

Clearly $d\mu/dx < 0$ for $x \in (0, 1)$. Which, in turn, implies that x is decreasing respect to μ .

Let's see now that (20) holds. When μ goes to 0, $x(\mu)$ converges to the only solution, $x(0)$, in the interval $(0, 1)$ of the equation $8x(0)^5 - x(0)^4 + 8x(0)^3 + 2x(0)^2 - 1 = 0$. Then $8x(0)^3 - 1 < 0$ which implies that $x(0) < 3/4$ as we wanted to prove. \square

Remark 3. As consequence of previous results there exist five-body PCC' s with m_1, \dots, m_4 in a CCcl or CCr configuration and $m_0 = 0$ is in the line perpendicular to plane containing m_1, \dots, m_4 passing by the mass center. These are examples of PCC' s which does not verify the conclusion of Lemma 6.2.

The configurations CCcl and CCr are bases of a PCC, with a vertex out of the plane, which do not verify the conclusion of Lemma 6.2.

Corollary 6.7. *For all admissible CC of 3-body or 4-body problem P has a synchronous solution.*

7 Non admissible central configurations

The following result shows a necessary condition for that a non-admissible CC allows a solution of the problem P .

Theorem 7.1. *We suppose that q is a non admissible CC and that the primaries are in a homographic motion, i.e. equation (1) is satisfied. Assume that the massless particle is moving on the z -axis with position vector $x_0(t) = (0, 0, z(t))$. Then, some of the following statement is satisfies:*

1. *The massless particle is in a stationary motion and*

$$\sum_{i=1}^n \frac{m_i q_i}{s_i^3} = 0, \quad (21)$$

i.e. the positions $0, q_1, \dots, q_n$ and the masses $0, m_1, \dots, m_n$ are in a CC.

2. *The $n+1$ -body system is in a homothetic motion. i.e. $Q(\theta(t))$ in the equation (1) is the identity matrix and $z(t) = cr(t)$, for some constant c . Moreover, the configuration q_0, \dots, q_n is a PCC, where $q_0 = (0, 0, c)$ and $m_0 = 0$.*

Proof. We recall the definition of the function f and line L from the Section 3.

The fact of the massless particle is moving on L , is equivalent to the condition $f(t, x_0(t)) \in L$ for all t , which, instead, is equivalent to the equality

$$\sum_{i=1}^n \frac{m_i r(t) Q(\theta(t)) q_i}{(r(t)^2 |q_i|^2 + z(t)^2)^{3/2}} = 0, \quad (22)$$

for every $t \in \mathbb{R}$.

With the same notation and following similar reasoning that in the proof of Theorem 3.2, we prove that

$$\sum_{j=1}^k \left\{ \frac{1}{(s_j^2 + (z(t)/r(t))^2)^{3/2}} \sum_{i \in F_j} m_i q_i \right\} = 0.$$

If $z(t)/r(t)$ would be a non constant function then previous equation and Lemma 3.3 would imply that q is admissible, which is a contradiction. Hence there exist $c \in \mathbb{R}$ such that $z(t) = cr(t)$. Now, we have two cases.

Case 1: $c = 0$. Then $z \equiv 0$ and (21) follows from (22).

Case 2: $c \neq 0$. From the motion equation for the massless particle and the Kepler equations (4), and the fact that $z(t) = cr(t)$ we have that

$$\frac{1}{r(t)^2} \sum_{i=1}^n \frac{m_i r(t)}{(s_i^2 + c^2)^{3/2}} = -\frac{\lambda}{r(t)^2} + r(t) \dot{\theta}(t)^2 \quad (23)$$

□

In this section we present an example that shows the condition of non-stacionarity in Theorem (3.2) is needed.

Proof Proposition ??. Some of the following calculations were made with symbolic math software. Let's consider a particular Euler's linear central configuration formed by three collinear bodies of mass $m_1 = 4 - \mu$, $m_2 = 2 + \mu$, $m_3 = 1$, where $0 < \mu < 1$, and $q_1 = 0$, $q_2 = 1$ and $q_3 = 1 + r$ their respective positions, with r such that

$$p(r, \mu) = 0,$$

where $p(r, \mu) = 6r^5 + (-\mu + 16)r^4 + (-2\mu + 14)r^3 + (-\mu - 5)r^2 + (-2\mu - 7)r - \mu - 3$. Note that as $p(0, \mu) = -\mu - 3$ and $P(1, \mu) = -7\mu + 21$ then, for all $0 < \mu < 1$, $r \in (0, 1)$. In this case the center of mass C is equal to $\frac{\mu}{7} + \frac{r}{7} + \frac{3}{7}$, so $C \in (0, 1)$.

We denote with x the point between 0 and 1 where the sum of the forces that the primary bodies make on a massless particle located in that position is equal to zero. For this value of x we have to $f(x) = 0$, where $f(x) = -\frac{4-\mu}{x^2} + \frac{\mu+2}{(-x+1)^2} + \frac{1}{(r-x+1)^2}$. Note that the left side of the previous equation is an increasing function that tends to $-\infty$ when x goes to 0, and tends to $+\infty$ when x goes to 1, so there is a unique point $x \in (0, 1)$, such that the equality holds.

Then, if we want to have a trivial solution of the problem (5) then necessarily C has to be equal to x . Let's see that there exists $\mu \in (0, 1)$ such that $C = x$, i.e. $f(C) = 0$. For this purpose, since C is a continuous function with respect to μ , we need to see that there exists a value $\mu_1 \in (0, 1)$ such that $f(C) < 0$ and $\mu_2 \in (0, 1)$ such that $f(C) > 0$. The function $f(x)$ can be factorized as

$$f(x) = \frac{Nf(x)}{Df(x)},$$

where $Nf(x) = 2\mu r^2 x^2 - 2\mu r^2 x + \mu r^2 - 4\mu r x^3 + 8\mu r x^2 - 6\mu r x + 2\mu r + 2\mu x^4 - 6\mu x^3 + 7\mu x^2 - 4\mu x + \mu - 2r^2 x^2 + 8r^2 x - 4r^2 + 4r x^3 - 20r x^2 + 24r x - 8r - x^4 + 10x^3 - 21x^2 + 16x - 4$ and $Df(x) = x^2(x-1)^2(r-x+1)^2$. Note that $Df(x) > 0$ for all $x \in (0, 1)$. If we consider $\mu = 0$ and compute $Nf(C)$ we have that

$$Nf(C) = \frac{r^4}{2401} + \frac{1514r^3}{2401} + \frac{2245r^2}{2401} + \frac{1110r}{2401} + \frac{333}{2401} > 0,$$

on the other, hand if $\mu = 1$ then

$$Nf(C) = -\frac{71r^4}{2401} + \frac{1486r^3}{2401} + \frac{401r^2}{2401} - \frac{1480r}{2401} - \frac{592}{2401} < 0,$$

because $0 < r < 1$. □

8 Recortes

Proof Theorem 3.2. We use a rotating coordinate system where the primaries are fixed. Concretely we put

$$\xi = Q(-\nu t)q.$$

In this system the motion equations are

$$\ddot{\xi} + 2\nu B\dot{\xi} + \nu^2 C\xi = \sum_{i=1}^n \frac{m_i(q_i - \xi)}{|q_i - \xi|^3}, \quad (24)$$

where

$$B := \begin{pmatrix} J & 0_{2 \times 1} \\ 0_{1 \times 2} & 0 \end{pmatrix}, \quad J := \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \quad \text{and} \quad C = \begin{pmatrix} -I_2 & 0_{2 \times 1} \\ 0_{1 \times 2} & 0 \end{pmatrix},$$

where $0_{n \times m}$ and I_n denote the null $n \times m$ matrix and the identity $n \times n$ matrix respectively. Assuming that the massless particle is moving on the z -axis then $\xi = q = (0, 0, z)$ and the Coriolis and centrifugal forces, $2\nu B\dot{\xi}$ and $\nu^2 C\xi$ respectively, are null. Therefore, taking account in the first two equation in (24) and identifying the vectors q_i , $i = 1, \dots, n$ with vectors in \mathbb{R}^2 , we have

$$\sum_{i=1}^n \frac{m_i q_i}{|q_i - \xi|^3} = 0.$$

Let $D = \{|q_i| : i = 1, \dots, n\}$. Suppose that $D = \{r_1, \dots, r_k\}$, with $r_i \neq r_j$ for $i \neq j$, and $\{1, \dots, n\} = F_1 \cup \dots \cup F_k$, where if $i \in F_j$ then $|q_i| = r_j$. Then

$$\sum_{j=1}^k \left\{ \frac{1}{(r_j^2 + z^2)^{3/2}} \sum_{i \in F_j} m_i q_i \right\} = 0.$$

Since we are considering a non-stationary solution, we have that $z(t)$ is not constant. Therefore there exists an interval $\mathcal{I} \subset \mathbb{R}^+$ where

$$\sum_{j=1}^k \left\{ \frac{1}{(r_j^2 + s)^{3/2}} \sum_{i \in F_j} m_i q_i \right\} = 0, \quad s \in \mathcal{I}.$$

Then, according to Lemma 3.3, we obtain (6).

If (6) is satisfied then the force field F acting on the massless particle carries the z axis in itself. Therefore, from the existence and uniqueness theorem and other elementary properties of system of ODEs we obtain a solution of (5) with $x(t) = y(t) = 0$. \square

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