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(71) Applicant(s)
Ian James Spark

(72) Inventor(s)
Spark, Ian

(74) Agent / Attorney
Ian James Spark, PO Box 12, Yinnar, VIC, 3869, AU

Gen 27 CAP **ABSTRACT**

The productivity of heavy trailers can be increased by increasing the load carried by each trailer and the number of trailers in the train.

To increase the load carried by each trailer we need to increase the number of axles in each trailer. The invention increases the number of axles/trailer, without increasing the scuffing conflict associated with axle groups with more than six parallel wheels.

The invention also reduces corner cutting by the rear of the trailers. This will allow the number of trailers in the train to be increased.

If articulation angles are positively controlled to their correct values, jack knifing of the train should be impossible.

The ability of the train to climb hills will be increased by positively driving all or some of the trailer wheels. However, if these are positively driven at the correct speeds, their steering effect will reinforce rather than conflict with the steering effects of the wheel angles and articulation angles.

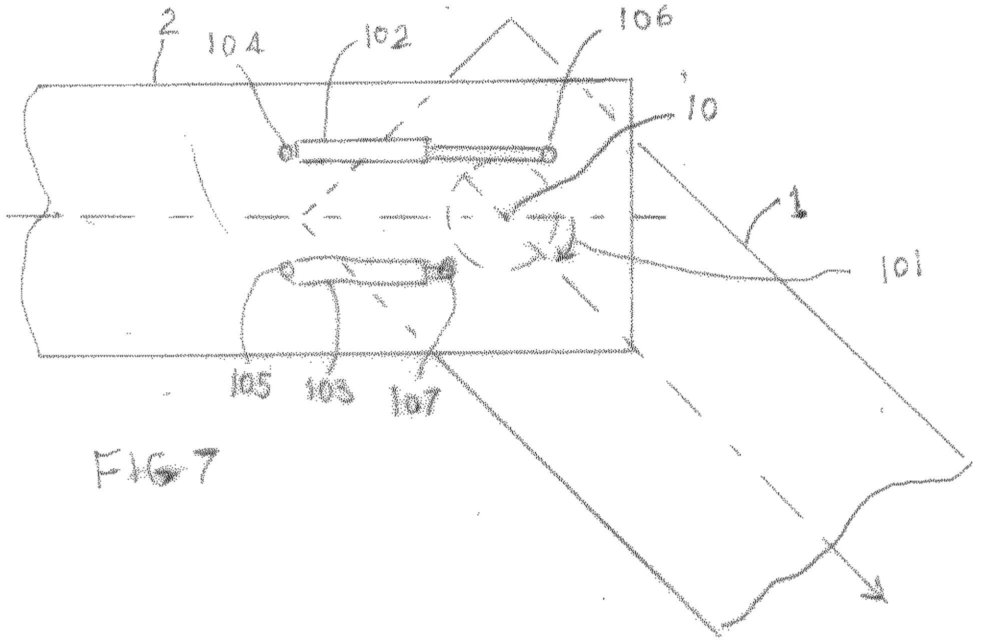
2
104
102
106
10
1
101
105
103
107

FIG 7

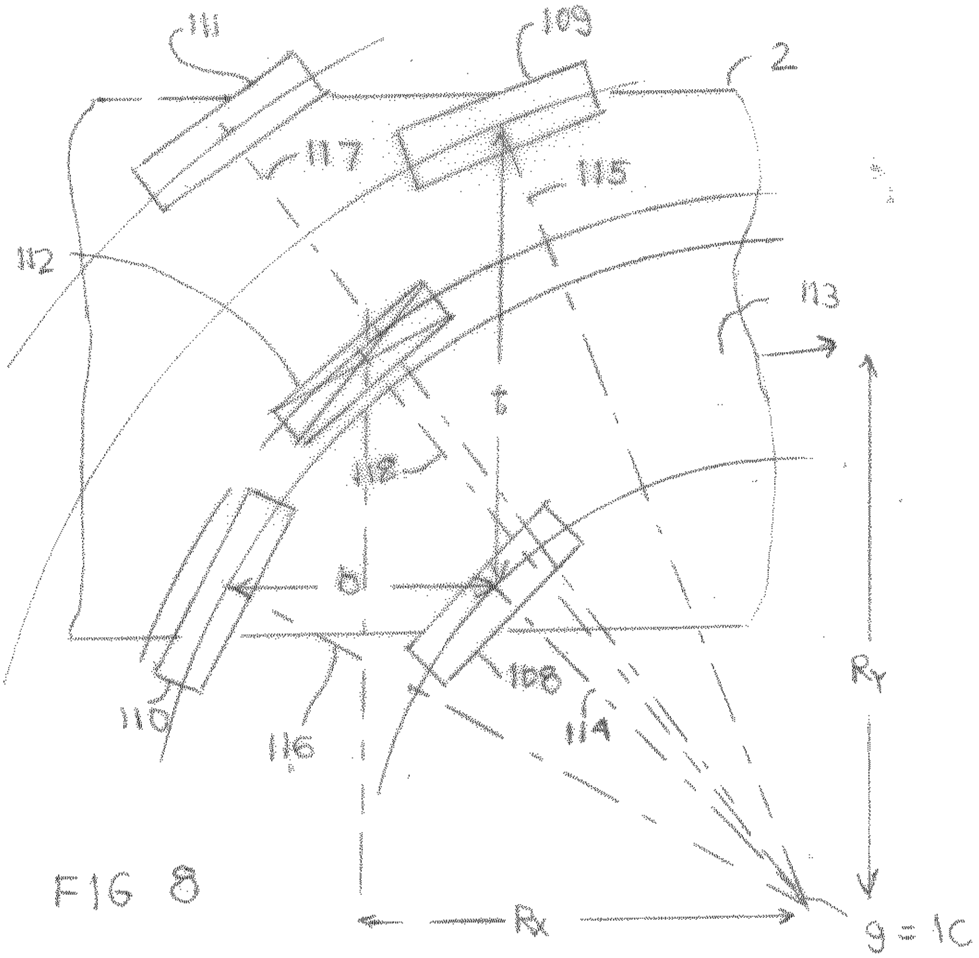
111
109
2
117
115
112
113
t
118
b
110
116
108
114
Ry
Rx
g = 1C

FIG 8

Gen 27 CAP

Means of increasing the productivity of heavy trailers.

Productivity can be expressed as the load that can be carried/prime mover or driver. For low density loads productivity may be expressed as volume carried/driver or prime mover.

Productivity can be increased by increasing the number of trailers in the train and the load (or volume) that can be carried by each trailer.

To increase the load/trailer we can increase the length of the trailer. Since there is generally a limit to the load on each axle, it is advantageous to increase the number of axles/trailer. However, increasing the number of axles with parallel wheels increases the conflict between the steering effects of the multiple wheels. Each combination of two wheels in an axle group produces a steering effect characterised by a theoretical instant centre (TIC). If there are N hubs in an axle group, we will have N(N-1)/2 theoretical instant centres. This conflict results in scuffing, which damages roads, wears the tyres and increases fuel consumption. Note that the energy required to damage the road and wear the tyres comes from burning more fuel. This conflict tends to be related to the slip angle of the tyres. This is inversely proportional to the radius of curvature of the turn.

The scuffing associated with two-axle groups is acceptable. Two-axle drive axle groups are common in prime movers and trucks.

The scuffing associated with three-axle groups is also acceptable. These are common in semitrailers.

However, the scuffing associated with four-axle groups is not generally acceptable. Therefore, if a fourth axle is added to the rear of a semitrailer it is "self-steered", passively steered or actively steered.

The term "self-steering" is misleading for the following reasons. Firstly "self-steering" axles are generally a pair of linked castors. They are intended to have little or no steering effect, so that they do not conflict with the steering effects of the non-steered wheels - which do have a definite steering effect. "Self-aligning" or "self-tracking" would be a more accurate adjective than "self-steering".

Since self-aligning axles can exert little or no cornering force on a trailer, all the required cornering force must be shared by the other wheels. This means we can only have one or two self-aligning axles/trailer. Otherwise, we would have a giant super-market trolly.

Passively steered trailer wheels are steered by mechanical linkages, usually activated by the articulation angle.

Actively steered trailer wheels are steered with electro-hydraulic systems. Two options are available.

Firstly, if one axle is unsteered, it becomes the master axle. The correct wheel angles for the other trailer wheels can easily be deduced in real time from the articulation angle. Now the required cornering force is shared between all the axles. In principle there is no limit to the number of axles that can be added to the trailer. In practice, the trailer wheel angle required increases with its distance from the master axle. Trailer wheel angles are usually limited to values less than +/- 20 degrees.
Secondly, we can apply the concept of "Virtual Rail" where a slave reference point on the semitrailer is made to follow the path of a master reference point located on the prime mover, or on a real or virtual semitrailer with unsteered wheels. This is only possible if all trailer wheels are steerable. Note that the Virtual Rail system can handle non-steady state turns where the prime mover and the trailers have

different instant centres. Note that passive steering systems involving mechanical linkages cannot handle non-steady state turns due to phase differences between the prime mover and the trailers in the train.

Note that the "Virtual Rail" system deduces in real time not only the correct trailer wheel angles, but also the correct articulation angles. If these correct articulation angles are enforced with a control system, jack-knifing should be impossible.
The “Virtual Rail” system can also determine the correct speeds of the trailer wheels. If the trailer has N’ positively driven wheels, it will be subject to N’ (N’ – 1)/2 drive wheel-speed steering effects, each characterised by a theoretical instant centre. If we control the speed of the drive wheels so that they all have the same instant centre we will avoid longitudinal slip. Ideally the drive wheel speed single instant centre should match the wheel angle single instant centre.

Assumptions, approximations, and compromises.

Strictly, groups of parallel wheels are only at the correct angles to avoid scuffing when the axle is travelling in a straight line in a straight-ahead direction, when the curvature of the path of the group of wheels is zero. For paths with non-zero curvatures, the correct wheel angles will need to be different in order to completely avoid scuffing. This would require a dedicated steering actuator for each wheel. Drive axles would require constant velocity joints.

In practice we accept the small amount of scuffing associated with two-axle groups with unsteered wheels. We also accept the scuffing associated with three-axle groups with unsteered wheels. However, the scuffing associated with four-axle groups with unsteered wheels is deemed unacceptable.

Strictly, the path of a prime mover with a two-axle drive group is kinematically indeterminate because the six-wheeled prime mover will have 6(6-1)/2 = 15 theoretical instant centres (TICs).

As a rigid body can have only one actual instant centre (IC), these 15 ICs will fight one another to determine the actual single instant centre. We could determine the actual IC - and thereby the path experimentally. Alternatively, we could use a software package such as Automatic Dynamic Analysis of Mechanical Systems (ADAMS) to deduce the actual instant centre - and thereby the path. Note that the accuracy of this numerical method requires that the correct tyre/terrain data files are used.

Alternately, we could use the "Bicycle Approximation". Here we assume that the path of the prime mover can be deduced from the angles of two notional (= non-existent) wheels. In this case the number of TICs = 2(2-1)/2=1 TICs. The front notional wheel is a non-existent wheel located midway between the two front wheels of the prime mover. To a first approximation, the angle of the notional front wheel would be the average of the angles of the left and right front wheels.

The rear notional wheel is located at the centre of the rear axle group (CRAG) of the prime mover. As for the four rear wheels of the prime mover, the notional wheel will be unsteered (i.e. fixed at zero degrees). This assumption presupposes that the four rear wheels are identical and carry the same vertical load.

Similarly, for the six-wheel, three axle group located at the rear of a semitrailer, we assume that the path of this axle group can be approximated by the path of a notional wheel located at the centre of the six wheels. This will generally be the midpoint of the second axle of the three-axle group.

Means of increasing the number of axles of a semitrailer without (unduly) increasing scuffing

Let us consider a semi-trailer 14 m long. Here length is defined as the distance between the forward articulation point and the end of the semi-trailer. Such a trailer could carry a 48-foot shipping container. Let us assume that the spacing between the axles of the semi-trailer is 1.5 m and the rolling diameter of the tyres is 1.0 m.

Figure 1 shows a semi-trailer with two unsteered axles and two steered axles.

Figure 2 shows a semi-trailer with three unsteered axles and two steered axles.

Figure 3 shows a semi-trailer with two unsteered axles and four steered axles.

Figure 4 shows a semi-trailer with three unsteered axles and four steered axles.

Figure 5 shows a schematic train where a second semi-trailer is attached to the first semi-trailer by means of a S-type coupling.

Figure 6 shows a train where a dog trailer (comprising a dolly and semi-trailer) is attached to the rear of the first semi-trailer by means of an A-type coupling.

Figure 1 shows the plan view of a prime mover **1** and four-axle semi-trailer **2** 50 degree into a 90-degree right hand turn. The path **3** of the Centre of the Rear Axle Group (CRAG) **4** of the prime mover **1** approximates to the Low Speed Swept Path (LSSP) width PSS turn. In the PSS test the outside of the left front wheel **5** of the prime mover **1** is made to follow a circular arc of 12.5 m radius. In Figure 1 the CRAG **4** of the prime mover is made to follow a 12.5 m arc. This simplifies the path somewhat.

The CRAG **4** moves up the Y axis until the CRAG **4** reaches the start **6** of the circular arc **3.** The front wheels **5** and **7** of the prime mover **1** are them snapped to a steady state angle **8,** which is held until the prime mover **1** has completed the 90-degree turn. The front wheels **5** and **7** are then snapped back to zero degrees. The path **3** of the CRAG **3** is therefore two mutually perpendicular straight lines connected by a tangential circular arc. When the CRAG of the prime mover **1** is on the circular arc **3** the instant centre **9** of the prime mover **1** is constant.

The path of the semi-trailer **2** is simplified by making the articulation point **10** coincide with the CRAG **4.** However, path errors will be small if the distance between the articulation point **10** and the CRAG 4 are less than 0.2 m. We use a variant of the Virtual Rail technique described and claimed by Spark in Australian Complete After Provisional (CAP) application 2021203310. Here the Master Reference point (MRP) is located on a virtual trailer with a single axle with unsteered wheels. This axle becomes the master axle **11.** We then superimpose the real semi-trailer on to the virtual semitrailer. The unsteered axle **11** becomes a two-axle or three-axle group. Extra axles **12** and **13** are added behind and/or forward of the unsteered axle group. The wheels on the extra axles are steered so that they have the same instant centre as the unsteered axle group **11.**

We deduce the path of the real semi-trailer **2** and the correct wheel angles for the extra steered axles in real time using the following method:

- We drive the prime mover **1** and trailer **2** so that the CRAG **4** of the prime mover **1** follows the desired path. The path comprises a straight line parallel to the Y axis, a circular path, then a straight line parallel to the X axis. The IC **9** of the prime mover **1** will be the centre of the circular arc. It is the intersection of the rotational axis of the notional rear wheel 4 of the prime mover **1** and the rotational axis of the notional front wheel **14** of the prime mover **1.**

- According to Kennedy's theorem, the IC **15** of the semi-trailer **2** must lie on a line passing through the articulation point **10** and the IC **9** of the prime mover **1.** This line **16** will hereafter be referred to as the Kennedy line.
- The path of the semi-trailer **2** will be determined by the location of the unsteered notional master wheel **17.** This wheel will always roll towards the articulation point **10.** We can therefore determine the trajectory (and path) of the notional wheel **17** by rolling the notional wheel **17** towards the moving articulation point **10** in small increments. The accuracy of this numerical method will increase as the size of the increments is decreased. A time increment of 0.005 seconds is recommended. We multiple this by the instant velocity of the CRAG **4** to deduce the distance increment.
- The instant centre **15** of the semi-trailer **2** is the intersection of the Kennedy line **16** and the rotational axis **11** of notional master wheel **17** . From the IC **15** of the semi-trailer **2** the correct angles for the rear **18, 19** and forward **20, 21** steerable notional wheels can be determined - since the rotational axes **13, 12** of these wheels must pass through the IC **15** of the semi-trailer **2.**

Prior to the CRAG **4** of the prime mover **1** reaching the circular arc **3,** the IC of both the prime mover **1** and semi-trailer **2** will be at infinity to the right (and left). When the CRAG **4** enters the circular arc **3**, the IC **9** of the prime mover **1** snaps to a fixed position (which is the centre of the circular arc) and the IC **15** of the semi-trailer **2** lies on the Kennedy line **16.** As the prime mover **1** moves along the circular arc **3,** the IC **15** of the semi-trailer **2** will move along the Kennedy line **16** towards the IC **9** of the Prime mover **1.**

If the prime mover **1** continued around the circular arc **3,** the IC **15** of the semi-trailer **2** would eventually coincide with the IC **9** of the prime move. This is the steady state condition.

However, we may never reach a steady state because as the prime mover **1** exits the 90-degree turn, the IC **15** of the semi-trailer2 begins to move along the Kennedy line **16,** but away from the IC **15** of the semi-trailer **2.**

Note that the end **22** of the semi-trailer **2** will initially swing out relative to the path of the CRAG **4** of the prime mover **1.** However, it will eventually swing.in. The notional master wheel **17** will always swing in relative to the path of the CRAG **4.** In Figure 1 the notional unsteered master wheel **17** is located on the longitudinal axis of the semi-trailer **2** 10.0 m behind the articulation point **10.**

An electro-hydraulic control system will be used to actively steer the two rear wheels of the trailer to match the correct angle of the notional rear wheel. Similarly, the front two wheels will be actively steered to match the correct angle of the notional front wheel. Note that all eight real wheels can exert both vertical and cornering forces on the semi-trailer **2.**

Figure 2 shows a semi-trailer **23** with five axles. This is similar to the four axle semi-trailer **2** shown in Figure 1, but the central unsteered two axle group has been replaced with a longer unsteered threeaxle group. In this case the notional unsteered master wheel **24** is located on the longitudinal axis of the semi-trailer **23** 9.0 m behind the articulation point **10.** The instant centre **25** of semi-trailer **23** is the intersection of the rotational axis **26** of the unsteered notional master wheel **24** and the Kennedy line **16.** The rotational axis **27** of a notional rear wheel **28** passes through the IC **25** of the trailer **23,** as does the rotational axis **29** of a notional forward wheel **30.** The path of the end **22** of the trailer **23** is **31.** The path of master notional wheel is **32.** An electro-hydraulic control system will be used to actively steer the two rear wheels of the trailer to match the correct angle of the notional rear wheel. Similarly, the front two wheels will be actively steered to match the correct angle of the notional front wheel.

Figure 3 shows a semi-trailer **33** with six axles. This is similar to the four axle semi-trailer **2** shown in Figure 1, but the rear and front steered one-axle groups have been replaced with longer steered two-axle groups. In this case the notional unsteered master wheel **34** is located on the longitudinal axis of the semi-trailer **33** 10.0 m behind the articulation point **10.** The instant centre **35** of the semi-trailer **33** is the intersection of the rotational axis **36** of the unsteered notional master wheel **34** and the Kennedy line **16.** The rotational axis **37** of a notional rear wheel **38** passes through the IC **35** of the trailer **33,** as does the rotational axis **39** of a notional forward wheel 40. The path of the end **22** of the trailer **33** is **41.** The path of master notional wheel **34** is **42.** An electro-hydraulic control system will be used to actively steer the four rear wheels of the trailer **33** to match the correct angle of the notional rear wheel **38.** Similarly, the front four wheels will be actively steered to match the correct angle of the notional front wheel **40.**

Figure 4 shows a semi-trailer **43** with seven axles. This is similar to the gix axle semi-trailer **33** shown in Figure 3, but the central unsteered two axle group has been replaced with a longer unsteered three axle group. In this case the notional unsteered master wheel **44** is located on the longitudinal **axis** of the semi-trailer **43** 8.0 m behind the articulation point **10.** The instant centre **45** of the semitrailer **43** is the intersection of the rotational axis **46** of the unsteered notional master wheel **44** and the Kennedy line **16.** The rotational axis **47** of a notional rear wheel **48** passes through the IC **45** of the trailer **43,** as does the rotational axis **49** of a notional forward wheel SO. The path of the end **22** of the trailer **43** is **51.** The path of master notional wheel **44** is **52.** An electro-hydraulic control system will be used to actively steer the four rear wheels of the trailer **43** to match the correct angle of the notional rear wheel **48.** Similarly, the front four wheels will be actively steered to match the correct angle of the notional front wheel **5O.**

Figure 5 shows a train where a second seven axle semi-trailer **53** is rotatably attached to a lead semitrailer **54** by means of a B-type coupling SS. The distance between the forward articulation point **10** and the rear articulation point **SS** is 14 m. The prime mover **1** is off the page to the right. The notional master wheel **56** is located on the longitudinal axis of the lead semi-trailer **54** 7.0 m behind the forward articulation point **10.** The IC **57** of the lead semi-trailer **54** is the intersection of a line **58** perpendicular to the longitudinal axis of the prime mover 1 and the rotational axis **59** of the master notional wheel **56.** A two-axle four-wheel axle group is located behind the master notional wheel. This axle group has axles **60** fixed perpendicular to the longitudinal axis of the lead semi-trailer 54, but with steerable wheels **61.** The steerable wheels **61** are actively steered so that they are parallel to a rear notional wheel **62,** where the rotational axis **63** of the rear notional wheel **62** passes through the **IC 57** of the lead semi-trailer **54.** A second rear notional wheel **64** is located close to the rear articulation point **55** of the lead semi-trailer 54. The rotational axis **65** of the second rear notional wheel **64** also passes through the IC **57** of the lead semi-trailer **54.** A four wheeled dolly **66** is rotatably connected to the rear of the lead semi-trailer 54 at the centre of the second rear notional wheel **64.** The dolly **66** is actively steered so that the wheels **67** of the dolly **66** are always parallel to the second rear notional wheel **64.**

A second 7-axle semi-trailer **53** is rotatably attached to the lead semi-trailer by means of a B-type coupling **55** located on the longitudinal axis of the lead semi-trailer **54** close to the second rear notional wheel **64.** A master notional wheel **68** is located 7.0 m behind the articulation point **55.** The rotational axis **69** of this notional wheel **68** is always perpendicular to the longitudinal axis of the second semi-trailer 53. The IC 70 of the second semi-trailer **53** is the intersection of the rotational axis **69** of the master notional wheel **68** and the Kennedy line **65** that passes through the articulation point **55** and the IC **57** of the lead semi-trailer **54.** An unsteered 3-axle 6-wheel axle group is centred on the master notional wheel **68.** The six wheels 71 of this group will always be parallel to the longitudinal axis of the second semi-trailer **53.** A rear notional wheel 72 is located on the longitudinal axis of the second semi-trailer **53.** The rotational axis **73** of this notional wheel **72** passes through the IC **70** of the second semi-trailer **53.** Wheels **74** are actively steered so that they are always parallel to the rear notional wheel 72. A second rear notional wheel **75** is located on the longitudinal axis of the second semi-trailer **53.** The rotational axis **76** of this notional wheel **75** passes through the IC **70** of the second semi-trailer **53.** Wheels **77** are attached to a dolly which is actively steered so that these wheels **77** are always parallel to the rear notional wheel **76.**

Figure 6 shows a train where an eight-axle dog trailer (comprising a two-axle dolly **78** and a six-axle semi-trailer **79)** is attached to the rear of the first six-axle semi-trailer **80** by means of an A-type coupling **81.** The distance between the forward articulation point **10** and the rear articulation point **81** is 14 m. The prime mover **1** is off the page to the right. A notional master wheel **82** is located on the longitudinal axis of the first semi-trailer **80** 7.0 m behind the forwaro articulation point **10.** The IC **83** of the first semi-trailer **80** is the intersection of a line 84 perpendicular to the longitudinal axis of the prime mover **1** and the rotational axis **85** of the master notional wheel **82.** A three-axle six-wheel axle group is located behind the master notional wheel **82.** This axle group has axles **86** fixed perpendicular to the longitudinal axis of the first semi-trailer **80,** but with steerable wheels **87.** The steerable wheels **87** are actively steered so that they are always parallel to a rear notional wheel 88, where the rotational axis **89** of the rear notional wheel **88** passes through the IC 83 of the first semitrailer **80.**

A two-axle four-wheel dolly **78** is rotatably connected to the rear of the first semi-trailer **80** by means of A-type coupling **81.** A master notional dolly wheel **89** is located at the centre of its four-wheel group. The IC **92** of the dolly is the intersection of the Kennedy line **90** passing through the articulation point **81** and the IC **83** of the first semi-trailer **80** and the rotational axis **91** of the master notional dolly wheel **89.** This intersection **92** is off the page.

A second six-axle semi-trailer **79** is rotatably attached to the dolly by means of a B-type coupling **93** located on the longitudinal axis of the dolly close to the master notional dolly wheel **89.** A master notional wheel **94** is located 7.0 m behind the articulation point **93.** The rotational axis **95** of this notional wheel **94** is always perpendicular to the longitudinal axis of the second semi-trailer **79.** The IC **96** of the second semi-trailer **79** is the intersection of the rotational axis **95** of the master notional wheel **94** and the Kennedy line **91** that passes through the articulation point **93** and the IC **92** of the dolly **78.** An unsteered three-axle six-wheel axle group is centred on the master notional wheel **94.** The six wheels **97** of this group will always be parallel to the longitudinal axis of the second semitrailer **79.** A rear notional wheel **98** is located on the longitudinal axis of the second semi-trailer **79.** The rotational axis **99** of this notional wheel **98** passes through the IC **96** of the second semi-trailer **79.** Wheels **100** are actively steered so that they are always parallel to the rear notional wheel **98.**

Note that the above numerical method does not require that the path of the prime mover is known in advance. Apart from dimensions, the only inputs required are the angles of the front wheels of the prime mover and the speed of its CRAG. It assumes that all the notional wheels roll with zero slip angles.

There are two methods of steering the real trailer wheels. The first is to convert a self-aligning trailer axle to an actively steered axle by replacing the anti-shimmy damper with a computer-controlled actuator. The problem with this means of steering the trailer wheels, is that the range of allowable trailer wheel angles is limited to a range of -20 to +20 degrees, and tight turns will require trailer wheel angles outside this range to avoid corner cutting and scuffing.

A second method of steering the trailer wheels is to attach the wheels to a dolly so that they are parallel to the longitudinal axis of the dolly and steer the dolly by means of a 8-type coupling. This means of steering the trailer wheels should allow the range of trailer wheel angles (relative to the longitudinal axis of the trailer) to be greater than -20 to +20 degrees.

Positive control of articulation angles

If we have a prime mover with N_P wheels and a semitrailer with N_T wheels then the prime mover will be subject to N_P (N_p – 1)/2 wheel-angle steering effects, each of which is characterised by a theoretical instant centre (TIC).

If the semi-trailer is connected to the prime mover at an articulation point the semitrailer will be subject to (N_T + 1) N_T/2 wheel-angle steering effects, each of which is characterised by a theoretical instant centre (TIC). Note that the articulation point is equivalent to a free wheel with zero slip – where its path is determined by the path of the prime mover.

However, if we lock the articulation point at a given angle, we convert the two rigid bodies into a single rigid body with N_P + N_t wheels. This single rigid body will now be subjected to (N_P + N_T)(N_P + N_T -1)/2 wheel-angle steering effects. Therefore, the increase in the number of steering effects acting on the train is;

$(N_P + N_T)(N_P + N_T -1)/2 - N_P(N_p – 1)/2 – (N_T + 1) N_T/2$

For the bicycle approximation, N_P = 2 and N_T = 1. In this case, the number of steering effects acting on the train increases from 2 to 3.

For a normal prime mover and semitrailer, N_p = 6 and N_T =6. Therefor for the unlocked articulation point, the number of wheel angle steering effects will be;

6(6 – 1)/2 + 7(7 – 1)/2 = 15 + 21 = 36. For the locked articulation point the number of wheel angle steering effects will be;

(6 + 6)(6 +6 – 1)/2 = 12(11)/2 = 66. This is an increase of 66 - 36 = 30 extra steering effects.

If we add a second semitrailer to form a B-Double train, for the unlocked articulation points the number of wheel-angle steering effects will be;

6(6 – 1)/2 + 7(7 – 1)/2 + 7(7 – 1)/2 = 15 +21 + 21 = 57.

If we lock both articulation points, the number of wheel angle steering effects will be;

(6 + 6 +6) (6 +6 + 6 -1)/2 = 153. This is an increase of 153 – 57 = 96 extra steering effects.

In a Cooperative Redundant Multiple Steering System, all the steering effects are made identical, so they have a single instant centre. Note that a rigid body can only have one actual instant centre.

Note that if we control the angle of all articulation points, then jack-knifing should be impossible.

Figure 7 shows a means of controlling the articulation angle. Prime mover **1** is rotatably connected to semitrailer **2** at articulation point **10**. The articulation angle **101** is -45 degrees. The articulation angle **101** is positively controlled by linear actuators or hydraulic cylinders **102** and **103**. One end of the actuators is rotatably attached to the semitrailer **2** at locations **104** and **105**. The other ends of the actuators are rotatably attached to the prime mover **1** at locations **106** and **107.**

Positive control of wheel speeds

Figure 8 shows a four-wheel two-axle group towards the rear of semi-trailer **2**. The desired instant centre of the semi-trailer **2** is located at **9**. The front right, front left, rear right and rear left wheel are **108**,**109**, **110** and **111** respectively. A non-existent notional wheel **112** is located at the centre of the four-wheel group.

We could drive all the wheels in a parallel wheel axle group at the correct speed of the notional wheel **112** located on the longitudinal axis of the prime mover or trailer. This would tend to drive the axle group in a straight line in the rolling direction of the notional wheel **112**. If all the drive-wheel speed steering effects are to have the same single theoretical instant centre as the wheel angle steering effects, then the speed of each drive wheel must be proportional to the distance between the centre of its contact patch and the common instant centre.

Figure 8 shows a four-wheel axle group of a semitrailer. A notional wheel **112** is located on the longitudinal axis of the semi-trailer **2**. The desired instant centre of the notional wheel **112** is **9.** This instant centre is located R_X ahead of the notional wheel **112** and R_Y to the right of the longitudinal axis **113** of the trailer **2**. The distance between the notional wheel **112** and the desired instant centre **9** is r_0. The wheelbase of the four-wheel group is b. The track of the wheel group is t. The track t is the distance between the contact patches of the right and left wheels. If ω_0 is the correct speed of the notional wheel, **112** then the correct speeds of the four trailer wheels are given by the following equations;

$\omega_n = \omega_0(r_n/r_0)$ where;

$r_{FR}^2 = (R_Y + t/2)^2 + (R_X – t/2)^2$;

$r_{RL}^2 = (R_Y - t/2)^2 + (R_X – t/2)^2$

$r_{RR}^2 = (R_Y + t/2)^2 + (R_X + t/2)^2$

$r_{FL}^2 = (R_Y - t/2)^2 + (R_X + t/2)^2$, where r_{FL} , r_{FR} , r_{RL} and r_{RR} are front right, front left, rear left and rear right trailer wheels respectively.

In Figure 8, we have turned the four wheels so that their rotational axes **114** to **117** all intersect at the instant centre **9**. The rotational axis **118** of the notional wheel also passes through the desired instant centre **9.**

Note that if we turn all the wheels in the group the same amount then, they will no longer roll in a direction that is perpendicular to the line passing through their contact patch and the common instant centre **9.** Some wheels will have positive slip angles and others will have negative slip angles. Wheel **109** would have the largest negative slip angle and wheel **110** would have the largest positive slip angle. We could overcome this problem by steering the four wheels by different angles, as depicted in Figure 8. However, we could this would require a dedicated steering actuator for each wheel.

If slip angles are small, the scuffing energy loss will be small. In this case we should compensate for the fact that the speed of the wheels around the instant centre **9** will be less than its speed in its rolling direction. Strictly we should divide the rolling direction wheel speeds by the cosine of the slip angles of the wheels.

In this case $\omega_n = \omega_0(r_n/r_0 \cos \alpha)$ where α is the slip angle.

The claims defining the invention are as follows:

Claim 1: A train comprising a prime mover rotatably connected to a semi-trailer at an articulation point, where the path of an unsteered notional wheel located at the centre of a rear axle group of the prime mover is determined by the angle of a notional steerable wheel located midway between steerable front wheels of the prime mover, where the instant centre of the prime mover is the intersection of the rotational axis of the notional front wheel and the rotational axis of the unsteered notional wheel located at the centre of the rear axle group of the prime mover, where a Kennedy line passes through the articulation point and the instant centre of the prime mover, where the instant centre of the semi-trailer is the intersection of the Kennedy line and the rotational axis of an unsteered notional wheel located on the longitudinal axis of the semi-trailer, where notional steered forward and rear wheels are also located on the longitudinal axis of the semi-trailer so that their rotational axes pass through the instant centre of the semi-trailer.

Claim 2: A train according to claim 1 where a four-wheel or six-wheel axle group is located on the semi-trailer where the longitudinal axis of the axle group is parallel to the longitudinal axis of the trailer and the centre of the axle group coincides with the centre of the unsteered notional wheel, and a two-wheel, four-wheel or six-wheel axle group is added to the rear of the semi-trailer, where the longitudinal axis of the rear axle group is parallel to the longitudinal axis of the semi-trailer and the centre of the axle cjoup coincides with the centre of the centre of the steered notional rear wheel, where the wheels of the rear axle group are actively steered so that their rotational axes are parallel to the rotational axis of the steered notional rear wheel.

Claim 3: A train according to claims 1 or 2 where a four-wheel or six-wheel axle group is located on the semi-trailer where the longitudinal axis of the axle group is parallel to the longitudinal axis of the trailer and the centre of the axle group coincides with the centre of the unsteered notional wheel, and a two-wheel, four-wheel or six-wheel axle group is added towards the front of the semi-trailer, where the longitudinal axis of the forward axle group is parallel to the longitudinal axis of the semitrailer and the centre of the axle croup coincides with the centre of the centre of the steered notional forward wheel, where the wheels of the rear axle group are actively steered so that their rotational axes are parallel to the rotational axis of the steered notional rear wheel.

Claim 4: A train according to claim 1 where a four-wheel or six-wheel axle group is located on the semi-trailer where the longitudinal axis of the axle group is parallel to the longitudinal axis of the trailer and the centre of the axle group coincides with the centre of the unsteered notional wheel, and a two-wheel, four-wheel or six-wheel dolly is added to the rear of the semi-trailer, the centre of the axle group coincides with the centre of the centre of the steered notional rear wheel, where the dolly is rotatably connected to the semi-trailer by means of an articulation axis that coincides with the centre of the steered notional rear wheel, where the rear dolly is actively steered so that the rotational axes of the unsteered wheels on the rear dolly are parallel to the rotational axis of the steered notional rear wheel.

Claim 5: A train according to claims 1 or 2 where a four-wheel or six-wheel axle group is located on the semi-trailer where the longitudinal axis of the axle group is parallel to the longitudinal axis of the trailer and the centre of the axle group coincides with the centre of the unsteered notional wheel, and a two-wheel, four-wheel or six-wheel dolly is added towards the front of the semi-trailer, the centre of the axle group coincides with the centre of the centre of the steered notional forward wheel, where the dolly is rotatably connected to the semi-trailer by means of an articulation axis that coincides with the centre of the steered notional forward wheel, where the rear dolly is actively steered so that the rotational axes of the unsteered wheels on the forward dolly are parallel to the rotational axis of the steered notional forward wheel.

Claim 6: A train according to anyone of claims 1 to 5 where the trajectories of the prime mover and the semi-trailer are deduced in real time from measurements of the angle of the front wheels and speed of the prime mover, by means of a numerical method.

Claim 7: A train according to anyone of claims 1 to 6 where the instant centres of the prime mover and the semi-trailer are deduced in real time from measurements of the angles of the front wheels and speed of the prime mover, by means of a numerical method, where the correct angles of the forward and rear steered notional wheels can be easily deduced.

Claim 8: A train according to anyone of claims 1 to 7 where electro-hydraulic control systems are used to make the angles of the rear and forward steered wheels identical to the correct angles of the rear and forward notional wheels.

Claim 9: A train according to anyone of claims 1 to 8 where a second semi-trailer is rotatably connected to the rear of the first semi-trailer at a second articulation point, where the trajectory of the second semi-trailer is deduced in real time from the trajectory of the second articulation point, the measured articulation angle and the location of an unsteered notional master wheel on the second semi-trailer, where the instant centre of the second semi-trailer is also determined, from which the correct angles for the steerable wheels on the second semi-trailer can be determined and implemented.

Claim 10 is a variant of claim 9 where the second semitrailer is replaced with a dog trailer comprising a dolly with unsteered wheels which is rotatably connected to the rear of the first semitrailer by means of a drawbar, where a second semi-trailer is rotatably connected to the dolly by means of a third articulation point, where the path of an unsteered notional wheel located at the centre of a rear axle group of the prime mover is determined by the angle of a notional steerable wheel located midway between steerable front wheels of the prime mover, where the instant centre of the prime mover is the intersection of the rotational axis of the notional front wheel and the rotational axis of the unsteered notional wheel located at the centre of the rear axle group of the prime mover, where a Kennedy line passes through the articulation point and the instant centre of the prime mover, where the instant centre of the dolly is the intersection of the Kennedy line and the rotational axis of an unsteered notional wheel located at the centre of the dolly axle group, where the instant centre of the second semi-trailer is the intersection of a second Kennedy line which passes through the second articulation point and the instant centre of the dolly, and the rotational axis of an unsteered notional wheel located on the longitudinal axis of the second semi-trailer, where notional steered forward and rear wheels are also located on the longitudinal axis of the second semi-trailer so that their rotational axes pass through the instant centre of the second semi-trailer.

Claim 11: A train according to claim 10 where a four-wheel or six-wheel axle group is located on the second semi-trailer where the longitudinal axis of the axle group is parallel to the longitudinal axis of the second semi-trailer and the centre of the axle group coincides with the centre of the unsteered notional wheel, and a two-wheel, four-wheel or six-wheel axle group is added to the rear of the second semi-trailer, where the longitudinal axis of the rear axle group is parallel to the longitudinal axis of the second semi-trailer and the centre of the axle group coincides with the centre of the centre of the steered notional rear wheel, where the wheels of the rear axle group are actively steered so that their rotational axes are parallel to the rotational axis of the steered notional rear wheel.

Claim 12: A train according to claims 10 or 11 where a four-wheel or six-wheel axle group is located on the second semi-trailer where the longitudinal axis of the axle group is parallel to the longitudinal axis of the second semi-trailer and the centre of the axle group coincides with the centre of the unsteered notional wheel, and a two-wheel, four-wheel or six-wheel axle group is added towards the front of the second semi-trailer, where the longitudinal axis of the forward axle group is parallel to the longitudinal axis of the second semi-trailer and the centre of the axle group coincides with the centre of the centre of the steered notional forward wheel, where the wheels of the rear axle group are actively steered so that their rotational axes are parallel to the rotational axis of the steered notional rear wheel.

Claim 13: A train according to claim 11 where a four-wheel or six-wheel axle group is located on the second semi-trailer where the longitudinal axis of the axle group is parallel to the longitudinal axis of the trailer and the centre of the axle group coincides with the centre of the unsteered notional wheel, and a two-wheel, four-wheel or six-wheel dolly is added to the rear of the second semi-trailer, the centre of the axle group coincides with the centre of the centre of the steered notional rear wheel, where the dolly is rotatably connected to the semi-trailer by means of an articulation axis that coincides with the centre of the steered notional rear wheel, where the rear dolly is actively steered so that the rotational axes of the unsteered wheels on the rear dolly are parallel to the rotational axis of the steered notional rear wheel.

Claim 14: A train according to claims 11 or 12 where a four-wheel or six-wheel axle group is located on the second semi-trailer where the longitudinal axis of the axle group is parallel to the longitudinal axis of the second semi-trailer and the centre of the axle group coincides with the centre of the unsteered notional wheel, and a two-wheel, four-wheel or six-wheel dolly is added towards the front of the second semi-trailer, the centre of the axle group coincides with the centre of the centre of the steered notional forward wheel, where the dolly is rotatably connected to the semi-trailer by means of an articulation axis that coincides with the centre of the steered notional forward wheel, where the rear dolly is actively steered so that the rotational axes of the unsteered wheels on the forward dolly are parallel to the rotational axis of the steered notional forward wheel. Claim 15: A train according to anyone of claims 10 to 14 where the trajectories of the prime mover and the semi-trailers are deduced in real time from measurements of the angle of the front wheels and speed of the prime mover, by means of a numerical method.

Claim 16: A train according to anyone of claims 10 to 15 where the instant centres of the prime mover and the semi-trailers are deduced in real time from measurements of the angles of the front wheels and speed of the prime mover, by means of a numerical method, where the correct angles of the forward and rear steered notional wheels can be easily deduced.

Claim 17: A train according to anyone of claims 11 to 16 where electro-hydraulic control systems are used to make the angles of the rear and forward steered wheels identical to the correct angles of the rear and forward notional wheels.

Claim 18: A train according to anyone of claims 1 to 17 where scuffing of the steerable wheels is reduced by dedicating one computer-controlled actuator to each steerable axle.

Claim 19: A train according to anyone of claims 1 to 17 where scuffing of the steerable wheels is further reduced by dedicating one computer-controlled actuator to each steerable wheel.

Claim 20. A train according to anyone of claims 1 to 19 where the articulation angles are positively controlled so as to transform the two or more linked rigid bodies into a single rigid body, where all the wheels in the single rigid body have a single instant centre.

Claim 21. A train according to anyone of claims 1 to 19 where the wheels of each rigid body are positively driven so that the drive-wheel-speed steering effects have a single instant centre, which coincides with the single instant centre of the wheel angle steering effects.

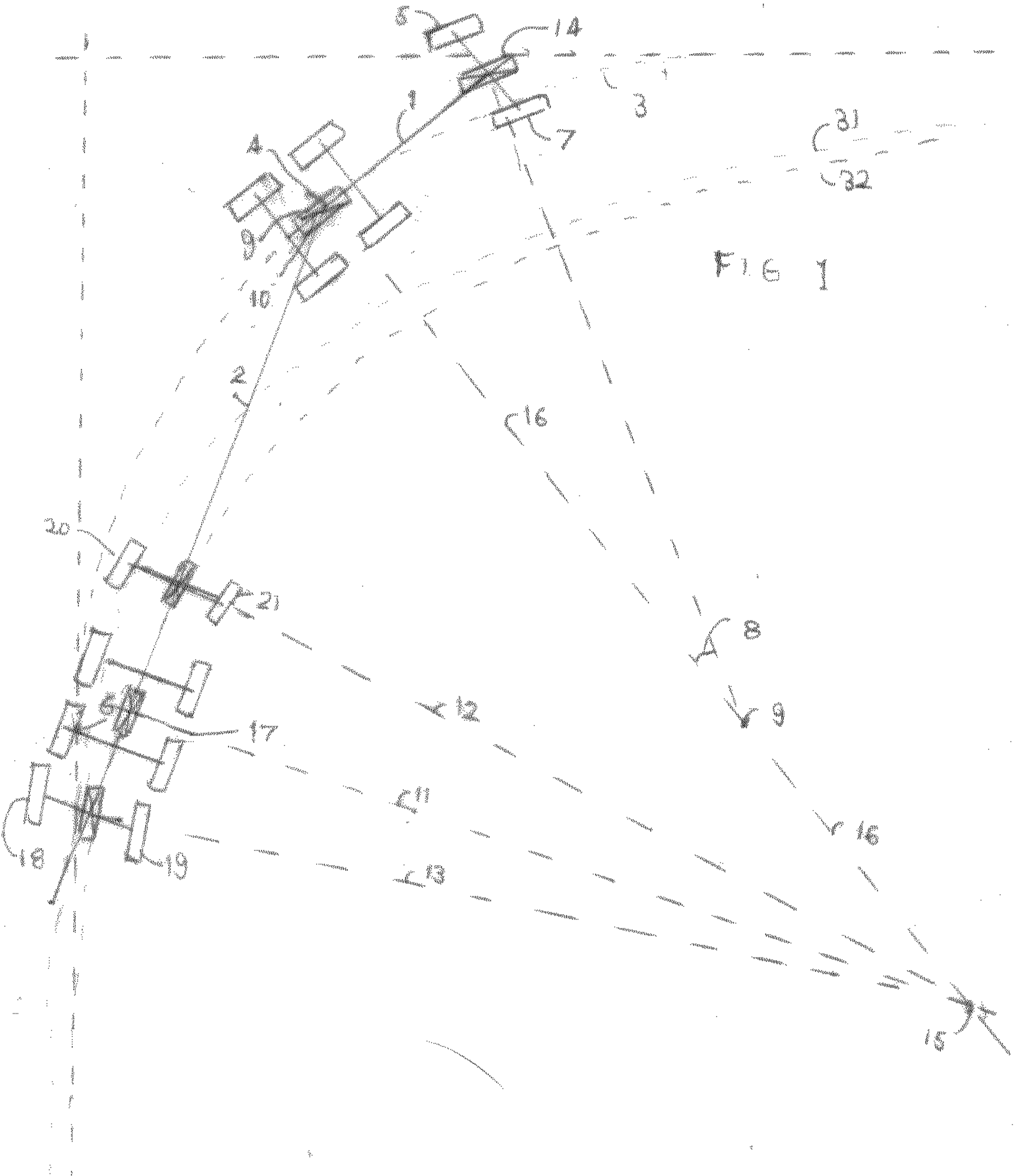

FIG 1

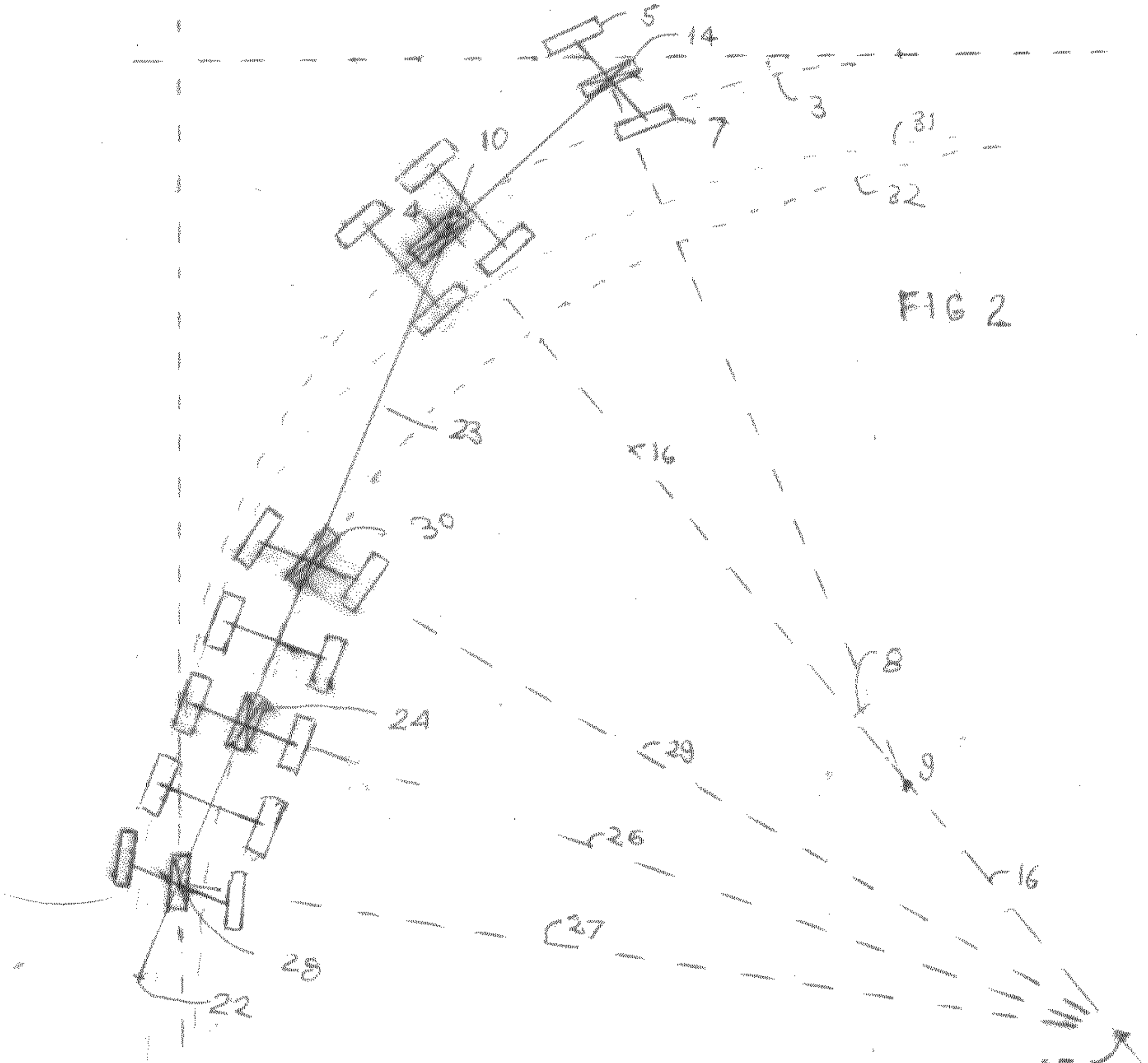

FIG 2

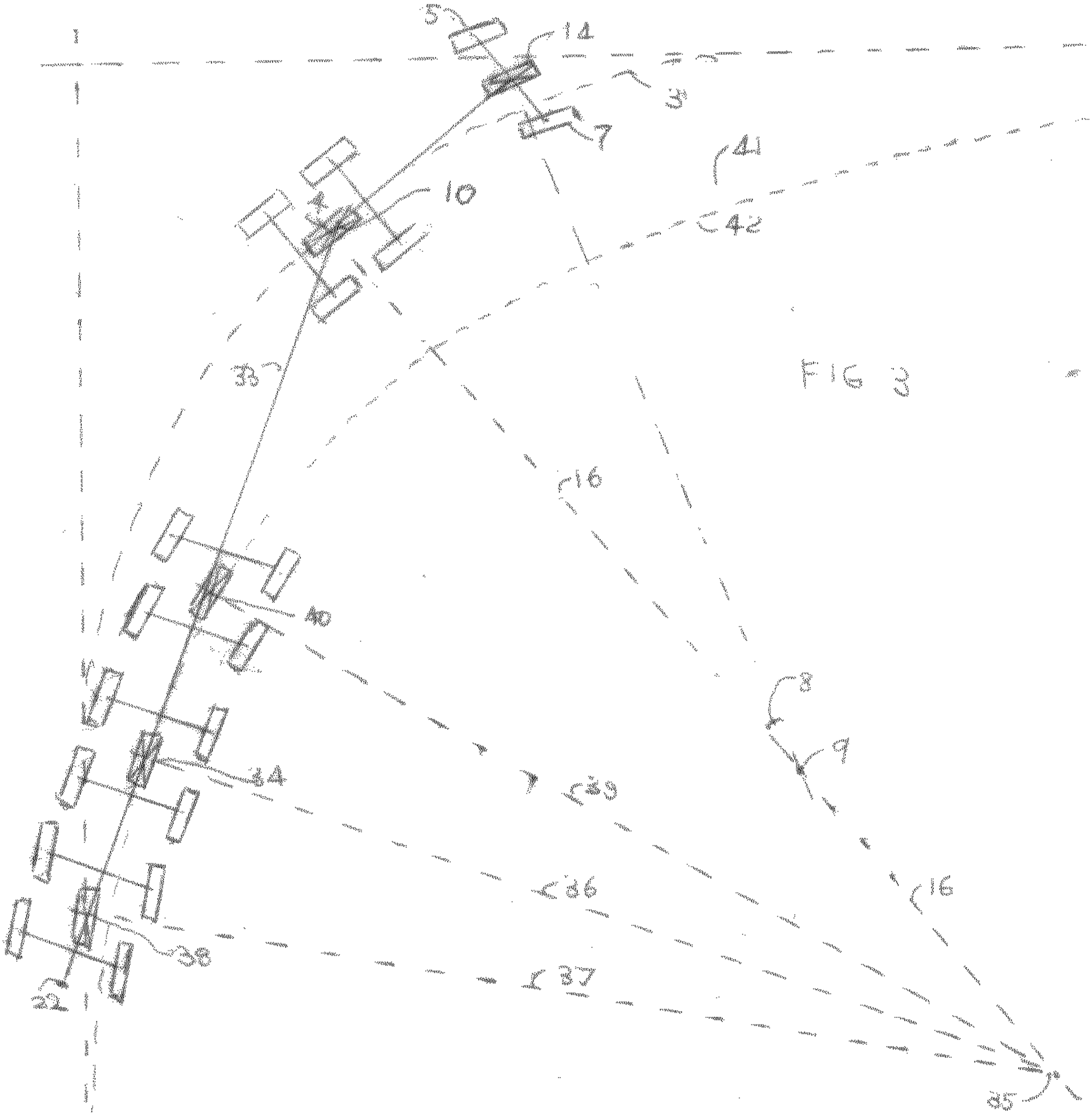

FIG 3

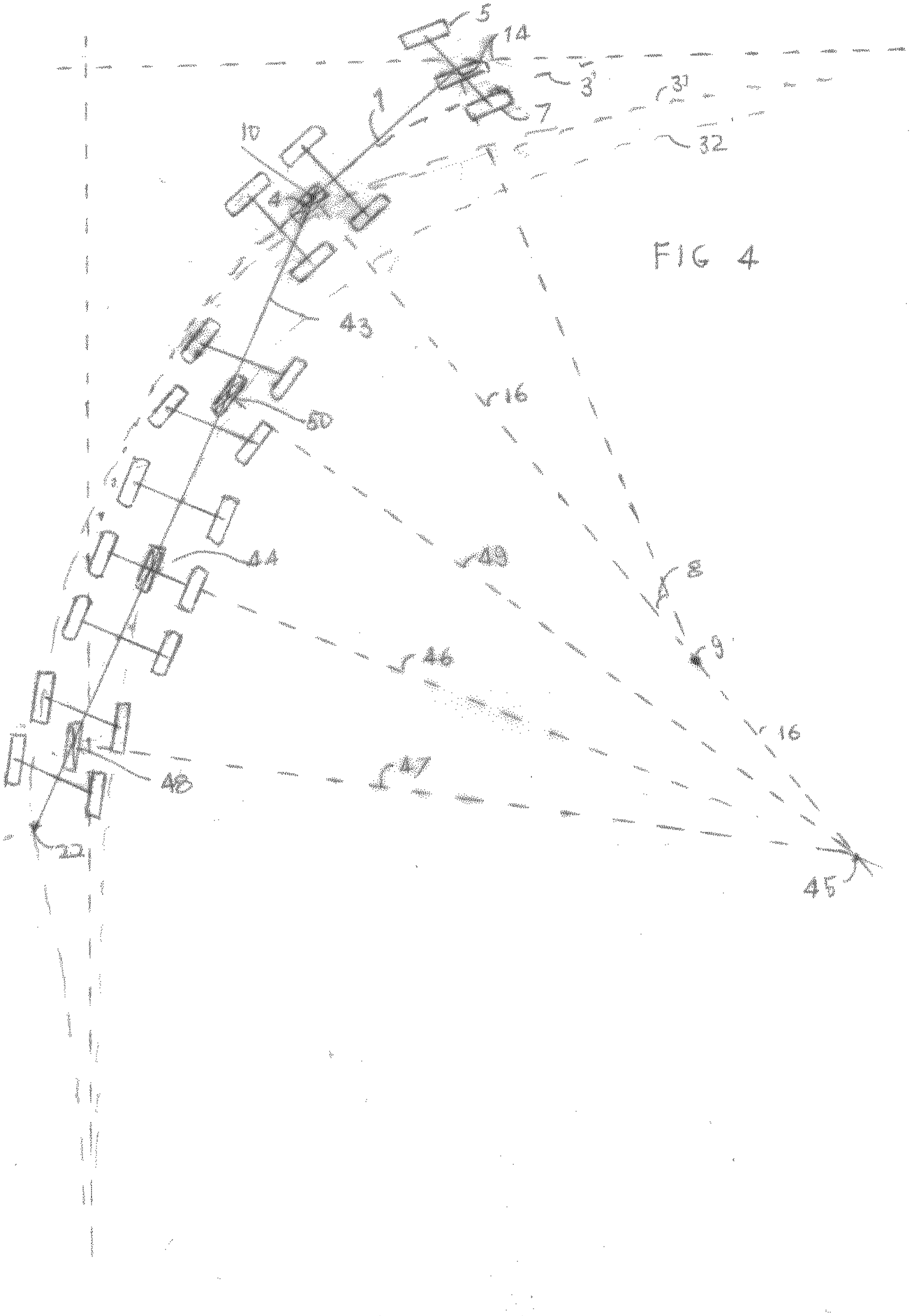

FIG 4

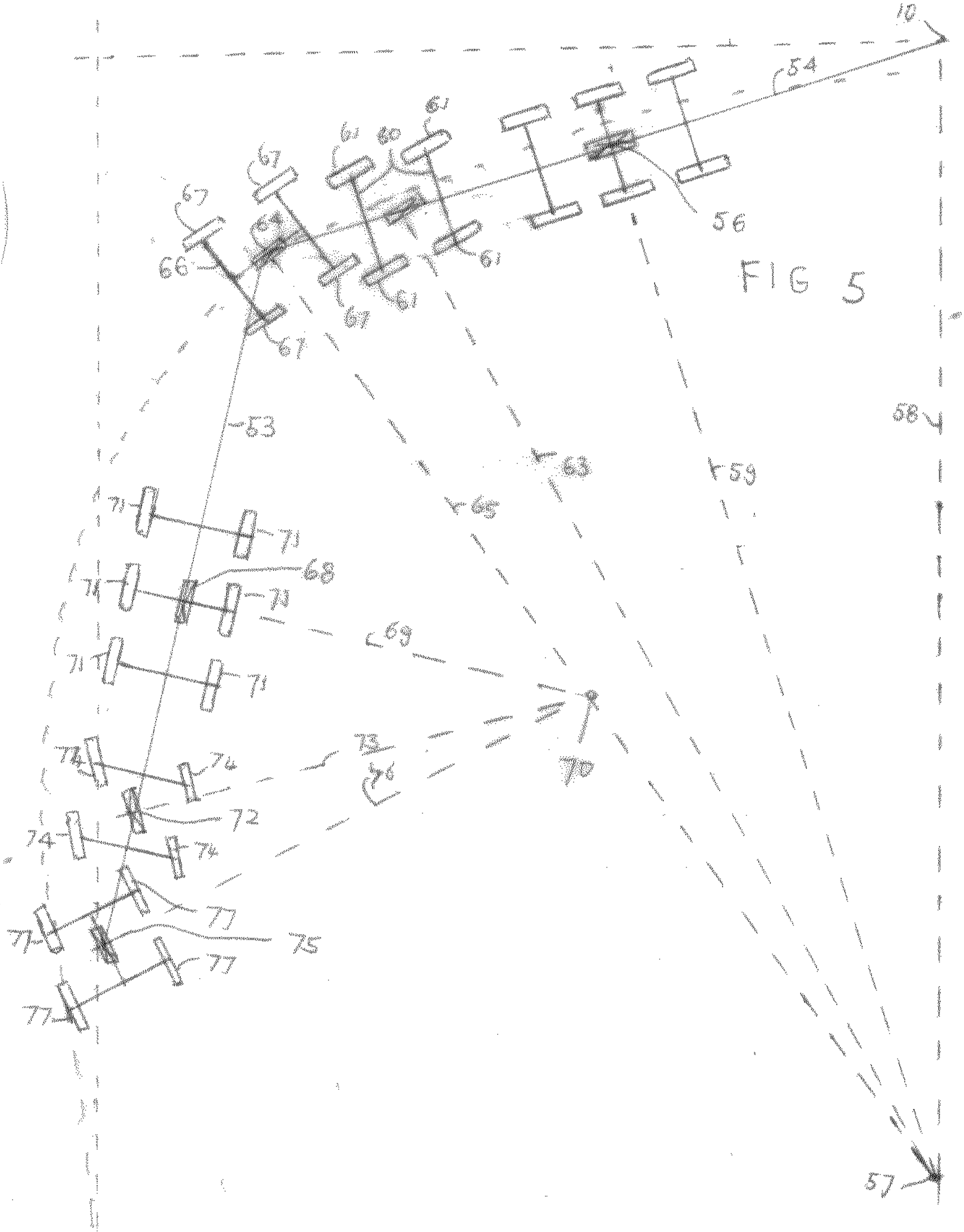
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FIG 5

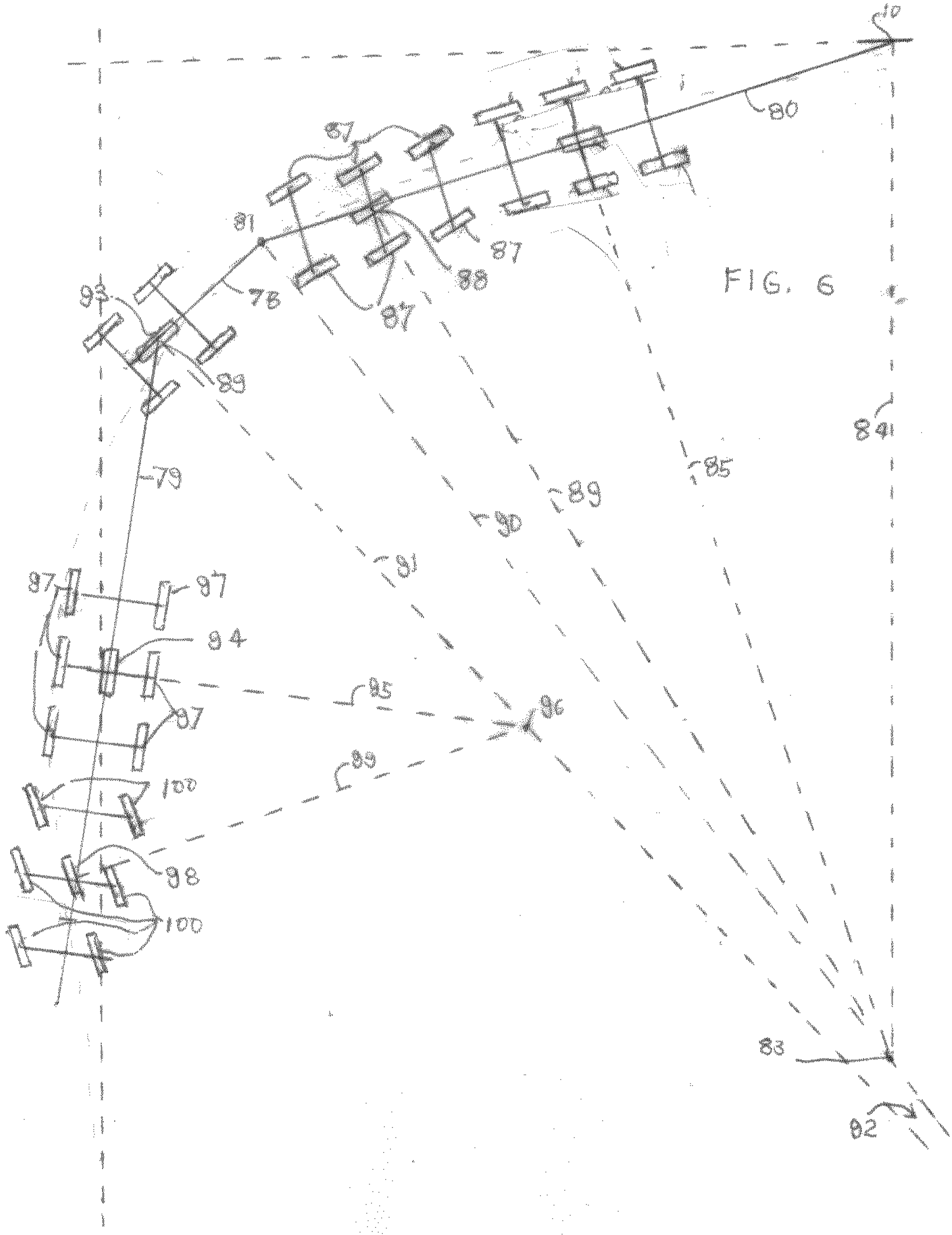
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FIG. 6

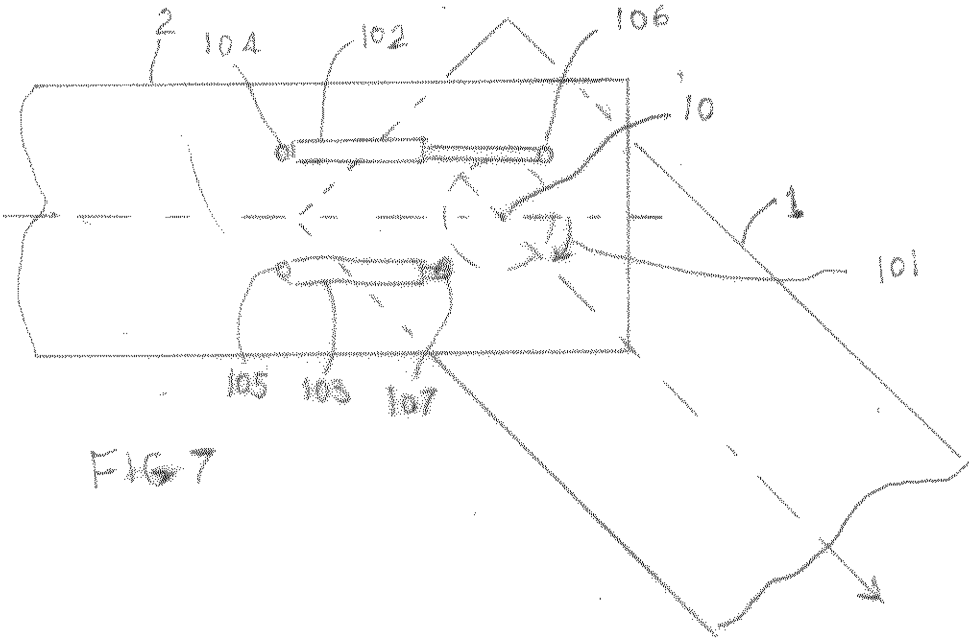
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FIG 7

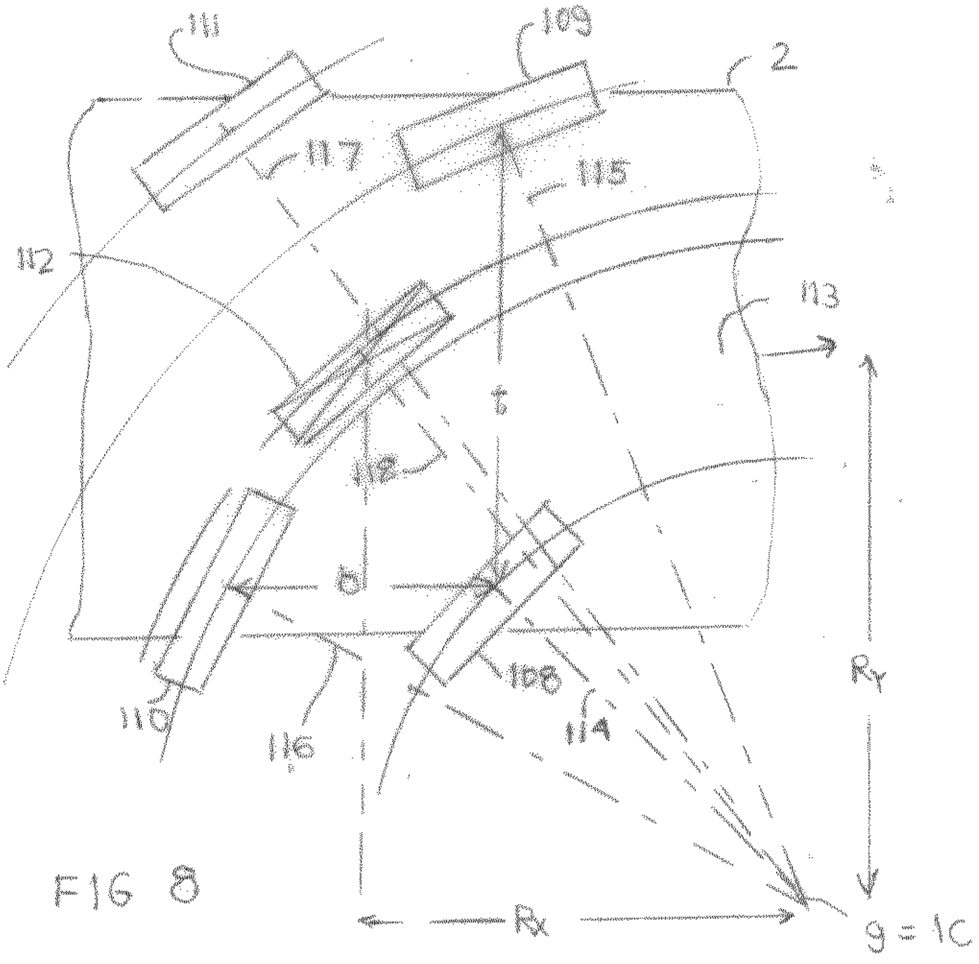
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FIG 8