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Proposal of an Advanced Facility to Perform Static and Dynamic Tests of Stability on Agricultural Machines

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The tests that are normally proposed to characterize the stability of an agricultural machine are substantially of two types: (1) static tests of lateral overturning of a vehicle in a straight-ahead configuration, (2) static tests of lateral overturning of a vehicle in a specific steering configuration. These tests have as output the maximum angle of lateral overturning of a vehicle, measured when all the vehicle's tanks are completely filled with their operating liquids and some weights are placed on the seat, to simulate the presence of the driver. There is also a third category of tests, less used, carried out via a system oscillating like a pendulum; the output of this test is the distance of the tractor's centre-of-gravity (COG) from the oscillation point, and, thus, the vertical position of the COG. All these tests suffer from evident limitations, hereinafter briefly explained, and stimulate us to conceive a completely-new test apparatus that can overcome these shortcomings. Limiting the attention to the conditions of static stability only, the above-presented tests do not allow providing the complete spatial position (in Cartesian coordinates) of the COG in relation to the vehicle's supporting base and, therefore, they prevent the prediction of the stability conditions of that vehicle when it travels on variously-inclined slopes and at angles with the maximum-slope direction different from the test conditions. Hence we design a first new-concept device, the *tilting turntable*, having the following characteristics: (1) the turntable has a circular shape and it is divided into quadrants capable of measuring the weight sustained by each of them due to the motionless vehicle positioned on them; (2) the turntable is installed on a tilting structure, and therefore it is able to simulate different gradients of the ground on which the vehicle is placed; (3) the turntable can rotate around an axis perpendicular to the surface supporting the vehicle, thus allowing to vary the angular position of the vehicle's longitudinal axis with respect to the maximum-slope direction of the tiltable structure. This equipment will allow precisely locating the COG of a vehicle and making many experimental (static) tests simulating a lot of working conditions of agricultural machines on slopes. Moreover, common stability tests do not take in any way into account the load-transfer phenomena related to the velocity factor, concerning not only the appearance of a centrifugal force applied on the COG, but also a readjustment of the machine's trim due to all the components having a certain elasticity (tires, suspensions where present, supports of the cabin) or having a degree of freedom in the plane transversal to the machine's longitudinal axis (suspended loads, liquids, inconsistent solids such as grain products, stacked solids such as pseudo-spherical fruits). The behaviour of a mobile system of this type, having a dynamically-variable trim, could be difficult to predict a priori by only knowing the position of the COG inquired under static conditions. For these reasons, we propose a second system that allows to investigate experimentally also these dynamic aspects by reproducing any real-scale manoeuvres in a controlled and safe environment. The proposed system is a *tiltable plane* with dimensions (about 15 x 15 m) allowing an agricultural vehicle to travel on it along complete circular paths.
By integrating the tilting turntable and the tiltable plane, a new innovative test rig has been created: the *tiltable platform*. It will be installed within the "*Agroforestry Innovation Laboratory*" of the Free University of Bozen-Bolzano, located at the upcoming "*NOI - Technology Park*".

1. Introduction

The typical real situations, in which a sideways overturning or a lateral rollover of an agricultural machine can occur, are basically three (Chisholm 1979; Coombes 1968; Guzzomi 2012), eventually concomitant:

- the machine is travelling across a gradient, in particular with a direction different from the maximum

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slope direction, on a support plane that is globally flat (but not horizontal);

- the tractor meets a local modification of the ground slope (Myers 2008), e.g. one wheel meets an obstacle in its trajectory or slides into a rut/a hole (i.e., the support plane is horizontal but not flat and, hence, it results to be locally not-horizontal and at least one wheel can lose the contact with the soil);
- the tractor attempts to execute an abrupt turn at an excessive speed (i.e., the centrifugal force deviates the weight force from the direction perpendicular to the support plane).

The extreme variety of situations that an agricultural machine can meet, above described, does not find an adequate match with the test-situations actually proposed by norms. Indeed, although all the illustrated real situations must be necessarily simplified and standardized to be investigated experimentally, the tests that are currently adopted to inquiry the rollover stability of machines, although simple and effective in their way of operating, have many basic deficiencies. For example, a vehicle, equipped with its own tires, with all the tanks completely filled with their operating liquids and loaded on its seat with some weights to simulate the presence of the driver, is placed on a inclinable flat platform and the angle of the platform necessary to have a side overturning of the vehicle is identified; it is to the angle corresponding to the loss of contact with the soil of the first wheel of the vehicle. This system has some limits: vehicles are tested under static conditions at the side-overturning only, with their steering members (wheels, central joint) in a configuration corresponding to a straight-path travelling (Figure 1), i.e. a very particular situation occurring during a machine's operating day. But turning manoeuvres are critical for the safety and deserve to be further investigated: the steering wheels (for conventional vehicles) or the two halves (for articulated vehicles) are angled and the supporting polygon could be considerably modified, especially for articulated tractors (Bietresato et al. 2015; Mazzetto, Bietresato & Vidoni 2013; Vidoni et al. 2015; Mazzetto et al. 2013). For articulated tractors in particular, the above-described test of static lateral overturning is therefore completed with another test, inspired by norms forecasted for telehandlers, pallet stackers, double stackers and order-picking trucks (UNI ISO 2012; UNI EN 2015): the tractor is placed on a tiltable platform in a specific turning configuration, geometrically determined by the passage of an internal wheel's axis of the part downward (the rear part of the tractor) through the centre of external wheel of the part upward (Figure 1). The platform is angled until the first wheel loses contact with the supporting plane. Although this is an advancement with respect to the lateral stability test performed in a straight-configuration only, as evident, the inquired turning configuration is too much specific both for the angulation between the two parts (geometrically fixed by tractor's dimensions) and for the relative position of the two halves of the tractor (with the front part upward).

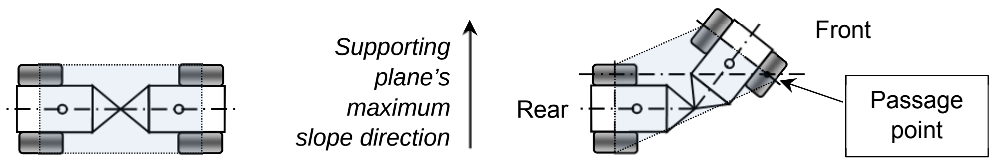

Figure 1: static stability test configurations actually forecasted for articulated farm tractors placed on a tilting plane with the support polygons evidenced; (left) straight-travelling configuration, (right) turning configuration with one of the internal wheel's axis passing through the centre of the external wheel of the part upward (UNI ISO 2012; UNI EN 2015); in this latter case the support polygon is highly distorted.

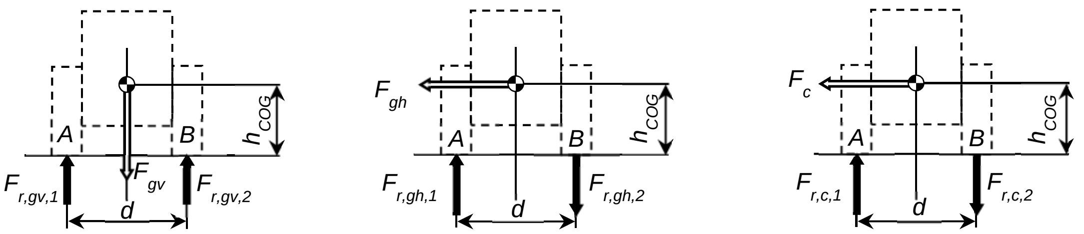

Figure 2: in a local frame of reference (i.e., aligned with the supporting plane, which could be inclined) and on a plane transversal to the vehicle's longitudinal axis, in black are evidenced the reactional forces due to the components of the gravity force perpendicular/parallel to the support plane (left/centre; when the side B higher than the side A; centre) or due to a centrifugal force during a turning manoeuvre toward the right side of the picture (right). When the overturning is incipient the vector sum in B is null. Vectors' lengths are not in scale.

Moreover, no dynamic term is kept in account in any stability test, whichever is the target-vehicle of the norm (agricultural tractor, telehandler, car, truck): all these norms regard static conditions only (UNI ISO 2012; UNI

EN 2015; ISO 1982, 2015). This is a serious limit of these tests because the speed (and the consequent centrifugal force) has a dangerous destabilizing contribution, especially when the centrifugal term and the weight-force component parallel to the supporting plane are directed toward the same direction, thus summing their moduli without any reducing trigonometric factor (Figure 2). The same centrifugal force could even alter the vehicle's mass distribution if some parts/systems (suspended loads, transported payloads) have the possibility to move transversally or, rather, are elastic (e.g., suspensions) and this could further worsen the situation. There is another condition that is potentially very dangerous: the execution of a turn upon a slope change (Figure 3). Indeed, this manoeuvre requires a sufficiently-wide second degree of freedom of the steering system (articulation joint, pivot axle) to prevent a possible loss of contact of one wheel and, hence, a situation of incipient quick variation of the vehicle's trim with a potential trigger of an overturning (the vehicle could lean on three wheels and be close to a balance situation).

Therefore, with the aim of overcoming the limitations of current systems, a new experimental facility for testing the static and dynamic stability of machines, has been developed and it is presented here.

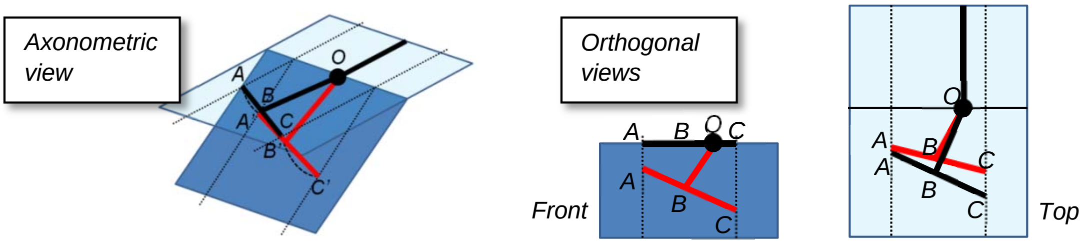

Figure 3: when an articulated vehicle is astride the edge (O: articulation joint), the front half/axle (ABC) has a double inclination (on the horiz. plane, to turn, and also due to the slope change); the dangerousness of this situation (A'B'C') is the impossibility for some vehicles to fully comply with the inclined plane, and hence the loss of contact of the wheel in C (C'); thick black/red lines: vehicle frame in the horizontal/inclined plane.

2. Concept, design and development of the new testing facility

A *top-down approach* has been applied for the present case: after having defined the requisites of a new test rig in term of tests to be performed, several systems able to perform each the tests stated are conceived separately and then merged together to obtain the new test facility. More in detail: (1) starting from the enumeration of the minimum requirements and the definition of the constraints to which the system is subjected, a list of technical specifications has been compiled (including: minimum dimensions, minimum achievable inclination angle); (2) then, the system has been delineated at increasing levels, some conceptual schemes and CAD drawings of some subsystems of interest have been drawn and, reasoning about their feasibility, some technical choices have been done (e.g., concerning the actuators); (3) working on simple schemes, a first kinematic study of the system has been performed to place the actuators in positions suitable for achieving the desired movements (here: partial rotations of some machine-members in correspondence to the elongation of the selected linear actuators). The detailed dimensioning of the system's components is instead a subsequent phase not addressed here (it will be let out on contract to an external design firm).

2.1 Individuation/formalization of the requisites for a new test rig

A new, innovative test rig must be able to give the analysts a higher level of knowledge concerning the vehicle in test than actual equipment, by performing static tests different than actual and dynamic tests, now not forecasted at all. Specifically, this facility should allow performing the following tests:

- *Static tests of a vehicle that is placed, motionless, on a plane with an increasing slope*; the vehicle's steering members (wheels, central joint) are in a configuration corresponding to a straight-path travelling or simulating a steering manoeuvre at whatever angulation degree; among these static tests:
  - o lateral/longitudinal stability test of a vehicle (classic tests of "*static lateral rollover stability*" and "*static longitudinal stability*", also called "*hopping test*"); the longitudinal axis of the vehicle is perpendicular/parallel to the maximum slope direction (and parallel/perpendicular to an isohypse);
  - o stability test of a stationary vehicle on a slope with the longitudinal axis of the vehicle differently angled (between -180° and +180°) with respect to the maximum slope direction of the support surface (test of "*global static stability*"); notice that this test includes also the previous tests: they corresponds respectively to an angle of ±90° and 0°/±180° of the vehicle's longitudinal axis;
  - o measurement of the load distribution, load transfer, trim change and downstream-tire(s) flattening in correspondence to several inclinations of the vehicle's longitudinal axis with respect to the max slope direction of the support surface (tests of "*global static load transfer*", "*frame's real inclination*", "*tires'*

deflection"); spatial positioning of the COG based on the loads supported by wheels;

- *Dynamic tests of a vehicle travelling at different speeds* (however close to real values) *along circular paths on a tilted plane with an increasing slope*
  - stability on a flat tilted plane ("*global dynamic stability on a flat plane*"); notice that, in this test, the tangent at each point of the circular trajectory has a different inclination, comprised in particular between -180° and +180° with respect to the maximum slope direction of the platform; this means that travelling along a complete circumference makes the tractor experience all the possible angles with respect to the maximum slope direction of the support surface
  - stability on a tilted plane having a sharp edge in its middle, hence having two slopes and a two-pitched-roof shape; by doing so, it is possible to simulate a steering manoeuvre with a change in the slope (i.e. a turn in counterslope), e.g. similar to a situation of a tractor entering/exiting from an interrow ("*global dynamic stability on a plane presenting an edge*").

The reference characteristics of a vehicle to be tested, useful for dimensioning the structures, are: mass of 7000 kg, minimum steering radius of 2 m, vehicle's supporting base dimensions of 3 m (width) × 5 m (length).

2.2 Definition of the facility's base features: static test equipment (the *"tilting turntable"*)

The *static tests* require basically a simple and flat inclinable plan, maybe wide enough to position the agricultural machine also with its longitudinal axis parallel to the maximum slope direction (a configuration not inquired by actual tests). The plan can be inclined by operating on its main frame, articulated at one end with the base, through a linear actuator according to a triangular pattern with a variable-length member (i.e., the actuator; Figure 4); from a kinematic point of view, the reference scheme is an articulated quadrilateral with three revolute pairs and a prismatic joint that causes the alignment between two members (corresponding to the piston and the cylinder of the used hydraulic jack); if the system will require a higher structural resistance, the indicated kinematic scheme could be eventually replicated by placing two actuators per side operating simultaneously and in parallel (i.e., positioned at the end and at half of the main frame, Figure 4).

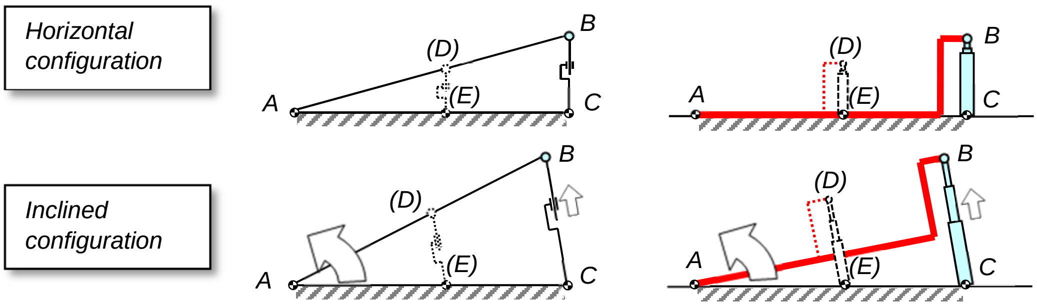

Figure 4: kinematic reference scheme and mechanism for generating the inclination of the support plane. The frame of reference is fixed to the ground on which the tiltable plan (i.e. the whole facility) is placed.

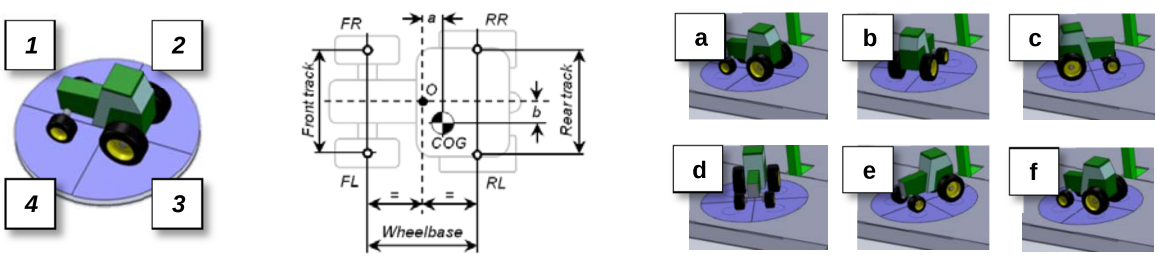

Figure 5: turntable predisposed with strain-gauges to measure the weight on each individual support (quadrant) at different inclination angles (left); the different weights (W_1-W_4) measured by the turntable's strain gauges are useful to localize the COG (distances a, b) with respect to the geometric centre O of the vehicle's support polygon (centre); measuring session for the global static stability test (pictures a-f; right).

However, it should be considered that a global static stability test on a conventional plan (i.e., only tiltable) requires the execution of many complete test-cycles as follows: positioning of the vehicle on the platform with the longitudinal axis of the vehicle differently angled, turning off of the engine, fastening of the vehicle on the plan, inclination of the plan until reaching the incipient overturning, restoring the horizontal position of the plan, unlocking of the vehicle, turning on of the engine, manoeuvring the vehicle to a new position… The repetitions of this sequence causes a significant drop of the efficiency of all the test procedure (requiring long times and high costs), and precludes to test every angular position of the vehicle's longitudinal axis (experimenters are forced to choose only some specific angles). Therefore, an innovative solution could be: making the (tiltable) support plane (and the vehicle positioned on it) rotate around a vertical axis by 360°, thus letting the system (called "*tilting turntable*"; Figure 5) explore with continuity (not only at a limited set of values) all angular positions of the vehicle's longitudinal axis with respect to the maximum slope direction. Furthermore, the static load transfer could be inquired by providing the support plane with sensors (a strain gauge per wheel) feeling the sustained weight of the vehicle (Figure 5); the downstream-tire(s) flattening by equipping both the support plane and the tractor with inclinometers or, alternatively, positioning a diastimeter per vehicle's corner.

2.3 Definition of the facility's base features: dynamic test equipment (the *"tiltable plane"*)

For executing the *dynamic tests* described before, the system requires a tilting plane allowing a vehicle (eventually, towing a trailer), to travel on it along complete circular trajectories. Indeed, travelling along a circumference allows a vehicle experiment with continuity all the possible positions of its longitudinal axis with respect to the maximum slope direction (between -180° and +180°), due to the different inclination of the tangent in each point of this trajectory. The requisite of having an inclinable plan (and a system required to operate it) is the same also for performing the static tests, with the only difference of the dimensions, in this case at least of 15 × 15 m because of the dimensions of an average tractor and the space needed for manoeuvring. The dynamic load transfer could be inquired by equipping each tire with a wireless pressure sensor (substituting the closing valve) and the tractor with an inclinometer fixed to the chassis.

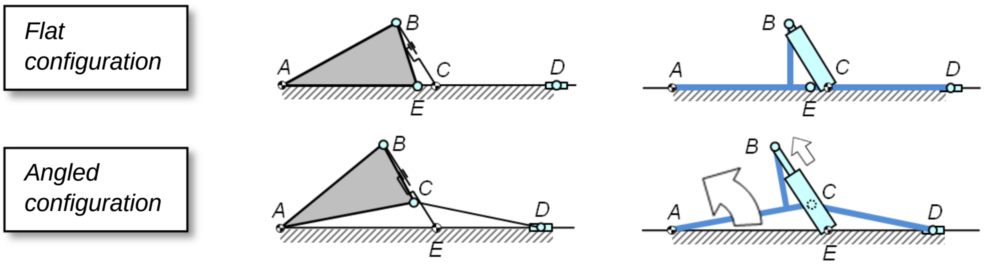

Figure 6: kinematic scheme (left) and mechanism for generating the angulation of the support plane (right); the frame of reference is fixed to the tiltable plan that is part of the facility (so it is a local frame of reference).

The creation of the *slope change* will be realized by an articulation hinge, positioned in the middle of the supporting surface and having an extension equal to the platform's width. This hinge will allow to angle the two flat parts that concur in it, thus making the support plane have a two-pitched-roof shape (Figure 6). The angle between the two half-platforms is obtained by acting on one half-platform only, and letting the second half-platform incline as a result of the configuration assumed by the first one (Figure 6); also in this case, the kinematic scheme proposed for the operated half-platform (driving the entire angling mechanism) is a triangle with a variable-length side (equivalent to an articulated quadrilateral with two members aligned and joined together by a prismatic pair); considering the complete angulation mechanism of the two half-platforms, however, it can be seen as an articulated quadrilateral with a degenerate member and one degree of freedom (morphologically similar to a centred crank mechanism), with three revolute pairs (i.e. the hinges) and a prismatic pair (the cursor/slide); the degenerate member is the slider with the hinge, since there is a null distance between the prismatic joint and the revolute pair superimposed to it.

2.4 Definition of the facility's features: merging of test subsystems to obtain the *"tiltable platform"*

The two systems, which have been delineated starting from the static/dynamic test requirements, will be part of the same test facility in the following way:

- as the mechanism for inclining the support plane will be used for both the types (static/dynamic) of test, it will be surely the main system equipping the facility and, therefore, it will act directly on the main frame of the facility (Figure 7A); this frame will support every other system, as well as the vehicle under test, and therefore should be sufficiently robust and operated by hydraulic jacks;
- the mechanism for angling the support plane has to be necessary placed upon the inclination mechanism, with the angulation hinge (*secondary hinge*) parallel to the inclination hinge (*primary or main hinge*) and the articulation of the lower half-platform placed in correspondence to the main hinge (Figure 7B);

- the turntable should be inserted in one of the two half-platforms (not astride the main hinge), preferably in the lower one to be closer to the access ramp to the tiltable plane on which the static/dynamic tests will be performed (Figure 7C, D).

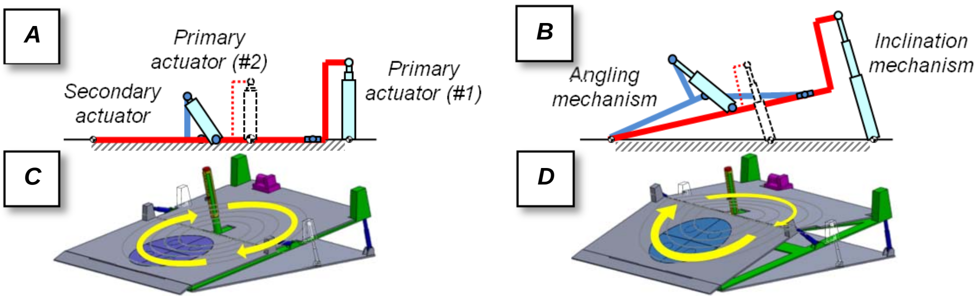

Figure 7: Schematic side views of the platform in a horizontal configuration (A) or tilted and angled (B). The tiltable frame is red, the secondary structure, necessary to generate the angle, is blue. If necessary, the final project can have another pair of primary actuators (#2) at about half of the support frame length. Axonometric views of the platform inclined only (C) or even angled (D); the turntable (in blue) has been inserted in the lower half-platform. The yellow arrows indicate a possible path to be travelled during a dynamic test.

3. Conclusions

Starting from a deep analysis of the requisites and using a top-down process, a new facility for testing the agricultural machinery's stability has been conceptualized and designed. It will be part of the permanent equipment of the *Agroforestry Innovation Laboratory* of the Free University of Bozen-Bolzano, located at the upcoming "*NOI - Technology Park*". The proposed system, called "*tiltable platform*", includes some interesting solutions for performing static tests different from actual (*tilting turntable*) and dynamic tests (*tiltable and anglable plane*). It will allow a global evaluation of the vehicles in tests both in static and in dynamic conditions (position of the COG, measurement of the load distribution, load transfer, trim change, downstream-tire(s) flattening), thus giving the analysts and the agricultural machines' designers a higher level of knowledge concerning the vehicles in test.

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