Harvesting Machines for crooked trees

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Summary: With today's harvesting heads, dealing with crooked trees remains a problem, although it becomes essential for economy in European forest. To face actual problems, modelling contacts between delimbing knifes and trunk can help to understand the real behaviour of harvesting machines during their work.

The first step was to characterize the problems on real existing heads, with photos, videos and measurements on real harvesting heads during operation.

In a previous work, a multi-body model of a harvesting head moving along a model of crooked tree has been made, with contacts between the trunk, rollers, delimbing knives and head frame. Although interesting results were obtained, some phenomena such as trunk and head flexibility could not be integrated and contact parameters were also difficult to identify.

Because of these limitations, a real demonstrator of a harvesting head was created to take into account all the real physical phenomena. It was built at a small scale to decrease the time and cost of development, still providing a good basis for comparing head architectures in future work. It was tested along a calibrated crooked trunk to evaluate its efficiency to pass across curves, and also to measure propelling forces of the rollers. Taking into account the effect of scale was a difficult problem, that was treated by using non-dimensional criteria.

This study finally allowed to characterize and to quantify the problems of current harvesting heads on crooked trees, in order to build future heads with better efficiency.

Keywords: Harvesting heads, Articulated heads, Tree feeding, Crooked trees, Contact multi-body modelling, Small scale demonstrator, ECOMEF project.

1. Introduction

By the year 2020, the French wood harvesting is expected to increase by 21 million m^3, among which 65% is hardwood [5]. However, most existing harvesting heads are dedicated to coniferous trees and lose their efficiency on hardwood, even leading to machine failure. In order to save time and money, lumberjacks are interested in harvesting heads achieving the same productivity on hardwood trees as on coniferous trees. The ECOMEF research project (Eco-design of mechanized equipment for hardwood harvesting) has the ambition to develop such heads.

The harvesting process with this kind of machines can be divided into four steps:

- First, the operator chooses a tree and places the head on the trunk base.
- Then, the machine cuts the tree, that falls down.
- When the tree is down, the machine delimbs the tree, until the length of the first piece of wood is achieved (Fig. 1a).
- Finally, the head cuts a part of the trunk at the desired length. Those two last steps are repeated until the end of the tree.

The typical harvesting head considered in this paper is the Kesla 25 RH [9]. It uses two propelling rollers and two pairs of delimbing knives that brace tightly the trunk (Fig. 1b). All the actuators are hydraulic.

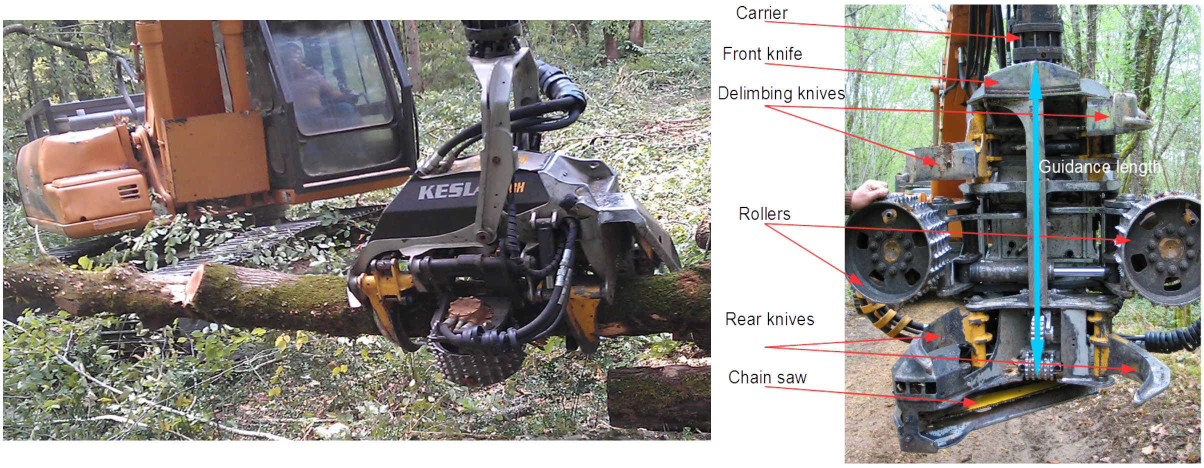


Figure 1: Example of harvesting head Kesla 25RH [9].
a) Harvesting head and its carrier; b) Description of components.

One strong limitation of this type of heads is that they cannot move smoothly on crooked trunks, that are very common with hardwood trees. Some experimental results [4] showed that the same machine could produce 1.4m^3/min for coniferous trees (fir) and only 0,5m^3/min for hardwood (beech). Typical problems are: 1- the head cannot delimb big branches; 2- the head passes trunk curves with difficulty, ripping and biting the wood and even getting locked (Fig. 2). This paper will focus only on the second problem, while delimbing is considered in a separate paper [2]. Providing a head with better motion abilities on crooked trees will contribute to increase productivity up to 40%, one of the main objectives of the ECOMEF research project.

After having proposed enhanced gripping devices [6], we will focus in this paper on the best ways to characterize performance along a crooked tree, and specifically evaluate the influence of the longitudinal distance between the contacts that guide the trunk in the head (roller-unit and one or two knife-units). Taking inspiration from some existing heads where the distance between delimbing and felling units is adjustable with a hydraulic cylinder [11], our head will be capable to adjust the distance between the roller-unit and the upper delimbing-unit.

Figure 2: Example of difficult motion and resulting wood rips along a crooked tree with a conventional head.

2. Multibody study

Before the modelling of the harvesting heads, the forces in the actual harvesting heads were measured for giving a basis of reference. A Kesla 25RH harvesting head was used [9] but it was not possible to get the position and hydraulic pressure of the actuators from the onboard computer. Placing additional sensors was difficult and Wi-Fi data acquisition was disturbed by radio interferences. Two force sensors were finally added to measure the delimbing forces on the knives [2]. Additional measurements using standard and high speed video cameras allowed to understand the machine behaviour on crooked hardwood trees and to give orders of magnitude. Overall, the cost of these experiments at full scale in term of time, human resource and money were rather high.

These measurements were re-used for constructing a preliminary 3D multibody model of a classical head on a crooked tree with Adams (MSC Software) [8]. This type of model can be parametrized easily and several types of kinematics can be evaluated. For this model, the considered performance indicator was the biting risk of the fixed knife onto the trunk. The model clearly showed the scrolling speed decrease of existing heads on crooked parts of the trunk. This type of model is interesting to get a preliminary idea of the physical behaviour of a machine but is very sensitive to inertial and contact parameters, that will require precise identification on additional experimental results.

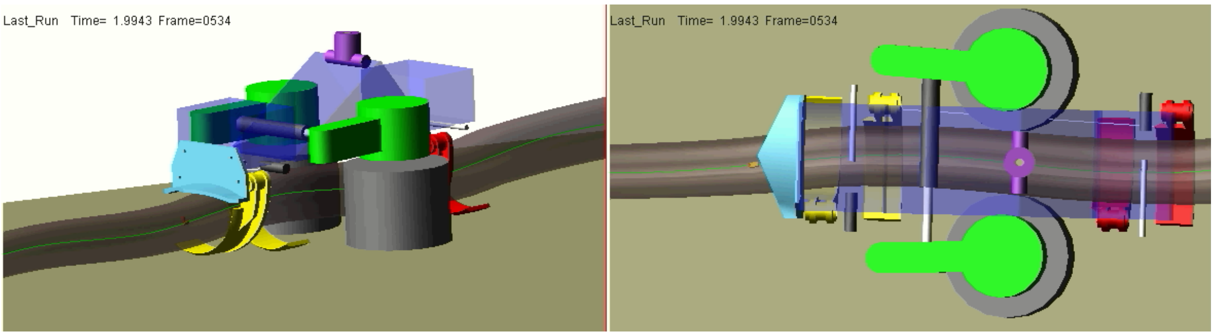


Figure 3: Adams multibody model of feeding on a crooked tree [8].

In order to evaluate the performance of harvesting heads on crooked trees, neither experiments at full scale nor multibody dynamic modelling gave complete satisfaction. Consequently, it was decided to complete the results with experiments at reduced scale on the demonstrator presented in the next section.

3. Scale effect and the small scale demonstrator

The insufficiencies of the presented numerical model and the cost and complexity of real machines at full scale were the reason to develop small scale demonstrators. The problem is that the relation connecting them to the full scale system is generally not fully proportional, but the overall behaviour of a small scale demonstrator approaches the behaviour of the full scale machine. The similitude theory and scaling laws can be used to map several experimental results at different scales [13].

This similitude theory is largely used in different fields. Different methods that allow to develop similitude laws are based on the Buckingham's Pi theory [1], which introduced the scaling numbers [3]. Using this similitude theory, many dimensionless numbers were extracted to characterize different systems, such as Reynolds number, Froude number, Blake number and many others [10]. The most important of these numbers are used in fluids mechanics and heat transfer fields.

This paper is about the feeding characteristics of harvesting heads and the possibility for these machines to pass crooked portions of trees. Among involved phenomena, roller rotation and roller-wood contact have to be considered. Roller rotation can be connected to the non-dimensional Torque Coefficient N. It represents the ratio between the torque delivered by a wheel and its speed and diameter modulated by its density. Several other numbers [10] can be used to characterize the roller-wood contact, in tribology (Adhesion Parameter N_{adh} , Coefficient of static friction f_s ,...) as well as solid mechanics (Force Numbers

N_F, Impact factor N_{imp},...) to model the gripping and delimbing forces.

The use of these numbers needs a fully instrumented demonstrator with different types of sensors. The demonstrator presented in figures 4 and 5 was constructed at scale 1:4 with respect to a real machine. In parallel with the presented demonstrator, a research is being conducted to find the appropriate dimensionless numbers that allow to validate the similarity between the small scale demonstrator and the real harvesting machine, and therefore, the results from the reduced scale will be extrapolated to the full scale.

The demonstrator was designed to perform the feeding action of a real harvesting head. It was essentially intended to study the effect of the distance named *guidance length* between two important sub-assemblies of the machine: the delimbing assembly and the feeding assembly (Fig. 4).

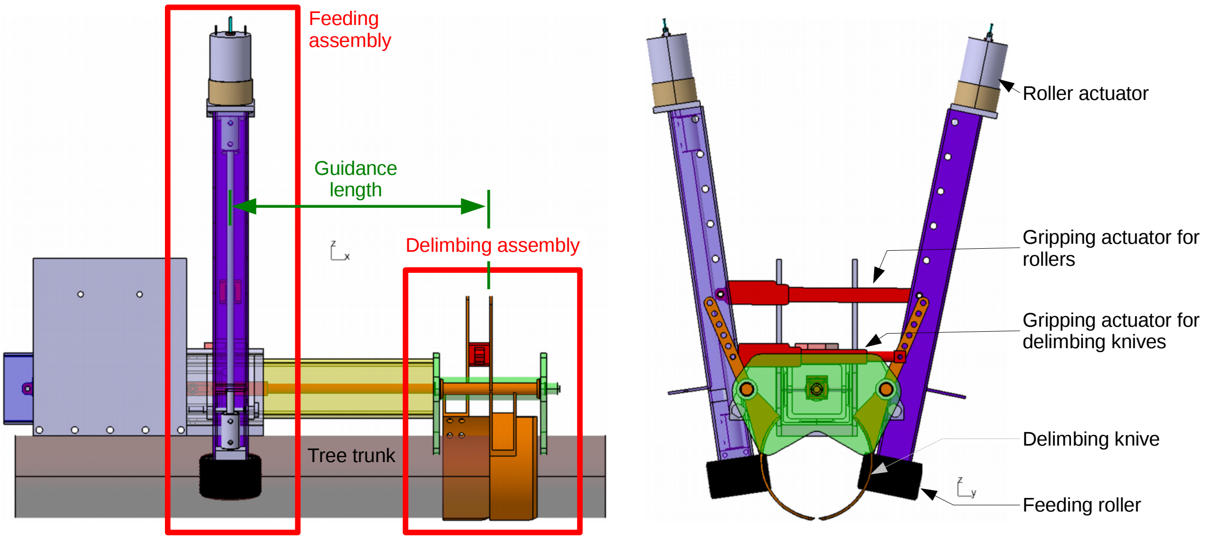


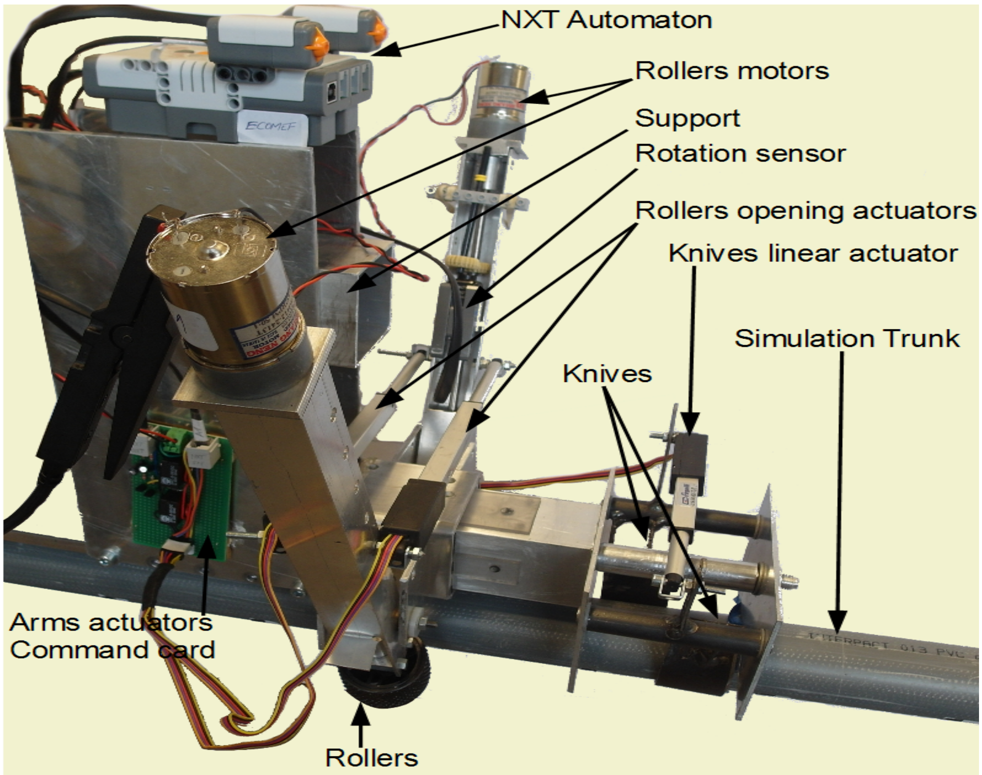
Figure 4: CAD model of the small scale demonstrator of harvesting head (side & top views).

The small scale demonstrator [7, 12] is intended to copy the actions of the real harvesting heads during the feeding task (presented in §1). The other tasks such as felling or delimbing are deliberately not considered here. For feeding, rollers and knives are first opened to allow the experimental tree trunk to be introduced manually. Once the trunk in place, both rollers and knives are closed. Finally, rollers motors are activated and the trunk scrolls of a fixed length through the demonstrator, which concludes the feeding task. An important experimental parameter is the guidance length, which can be modified easily.

The actuation of the demonstrator was performed by means of electric motors for the feeding rollers and electrical linear actuators for gripping functions. As for the information feed-back, the linear actuators Firgelli L16 are equipped with a potentiometer position sensor and the motor speed is captured by an angular speed sensor. Electric current and voltage of the two motors are also measured to evaluate the power used during the feeding of the trunk. The test campaigns were also filmed with a high speed camera in order to get the feeding speed of the trunk and detect different phenomena that occur during the tests.

The control of the platform is performed by an automaton taken from a NXT Lego Mindstorms robotic kit. It was chosen for its great range of modular parts and compatible sensors and actuators. The linear actuators L16 required an additional home-made electronic board for proper control with the NXT.

The control program is a sequential program divided into four sub-programs: rollers actuation, guidance length adjustment, opening of rollers and opening of knives. For the last two parts, a closed loop function is implemented for the precise gripping of knives and rollers. Sub-program selection is made by the built-in buttons of the NXT whereas sub-program execution is fired by external buttons (contact sensors).



F*igure 5: Small scale harvesting head prototype.*

4. Experimentation and results

After having been implemented and successfully tested with no load, the demonstrator was then experimented in different configurations through an extensive test campaign, summarized by the following script:

*For an **initial configuration** of the demonstrator, do*
*For a **guidance length** of the demonstrator, do*
*For a specified **experimental trunk**, do*
*For a specified **openings of rollers** and/or knives, do*
– *Activate rollers motors*
– *Save data for all sensors*
End For;
End For;
End For;
End For;

with the following parameters:

– *Initial configuration* is a combination of three settings: head fixture (fixed or balancing); trunk support (with or without); and a specified length that the trunk has to go through before stopping the roller motors. For the test campaigns, the demonstrator was fixed under a table and the finish line was a wall, which made the trunk always stop at the same distance (1400mm).
– *Guidance length* (Fig. 4) measures the distance between the gripping planes of rollers and knives. It depends on the actuator length (0-140 mm). Three discrete lengths were selected: 71 mm (normal); 5 mm (shorter); 143 mm (long harvesting head).

- *Experimental trunk*: The used trunks have two different parameters:
  - Trunk shape: straight or crooked. Two hardened PVC tubes of 2m each were used. The first one was used in its original state and the second one was hot-bent to respect a 10% lateral deviation, *i.e.* 10 cm/m. The tubes were finally marked with patterns to be used as landmarks for video processing (Fig. 6b).
  - Adherence coefficient: with / without rubber covering for improved friction (similar to the tree bark). After the first tests, the covering was removed (important resisting torque for the roller motors that prevented trunk feeding).

Figure 6: Calibrated trunk models used for experiments.
a) Coated crooked trunk; b) Uncoated straight trunk with patterns used as landmarks.

- *Opening of rollers*: These parameters are controlled by the program through the built-in NXT buttons. Two configurations were tested: 78 and 71mm. This distance depends on the linear actuator responsible for the opening of rollers.

The results of the tests are represented in Table 1, including the time of the passage, the mean power consumed during the test and the corresponding mean torque. The tested crooked trunk was oriented such that its plane is horizontal.

Effect to observe	Trunk	Guidance length (mm)	Rollers opening (mm)	Time of passage (s)	Mean power (Watts)	Mean torque (N.cm)
Guidance length	Straight	143	78	7,3	5,96	33,47
		71		6,99	5,48	30,14
		5		7,45	6,51	36,55
Opening of rollers	Straight	71	78	6,99	5,48	30,14
			71	6	4,12	21,84
	Crooked		78	8,37	6,82	38,7
			71	5,63	3,68	19,37
Passing horizontal flexuosities	Crooked	143	71	6,17	4,1	21,69
		71		5,63	3,68	19,37
		5		7,7	7,21	40,48

Table 1: Results of the test campaign.

Through these tests, three important observations were made:

- *Effect of the guidance length*: the tests showed that the optimal guidance length of the demonstrator that allows the feeding of the trunk with less time, torque and power is the guidance length of 71 mm. 143mm provides average results whereas 5mm can require twice the mean torque as 71mm along a crooked trunk. It was initially expected that the longer the guidance length, the shorter and easier the feeding action, but the tests results indicated otherwise. This can be explained by the fact that, in the beginning of the feeding, the trunk is horizontal and overhanging because not maintained vertically. Therefore the contact forces with the rollers generated by the overhanging trunk are high, which give some difficulties for the first part of the trunk feeding.

- *Effect of the opening of the rollers*: First, the configuration with an opening of 78mm was tested. This configuration gives an important gripping of the rollers on the tube. All the tests about the straight trunk were successful. On the contrary, the crooked trunk was difficult to feed with this configuration except for the average guidance length. The second configuration (71mm) was more favourable for trunk feeding and enhanced the feeding time and the power consumption not just for the crooked trunk but also for the straight trunk.

- *Passing horizontal curves*: For the first configuration of the rollers opening, only with a guidance length of 71mm that the demonstrator managed to pass the crooked trunk. After, and with adequate rollers op penning, the demonstrator successfully passed the crooked trunk. This performance can be explained by the fact that with an excessive gripping, the trunk is not free between the rollers and when the curve comes, the rollers can not follow it and therefore are blocked.

Throughout the performed tests, other points were observed concerning the general behaviour of the demonstrator, the most important ones being:

- The crooked trunk with a vertical orientation of its plane couldn't be passed in any of the tested configurations. The most encouraging results were with the shortest guidance length. Additional tests will have to be performed with different initial conditions.
- The number of the combinations tested of different parameters were not sufficient to affirm and generalize the results obtained by the demonstrator for specified factors.
- The over-tightening and the slipping of the rollers caused the abrasion of the used trunks and rubber covering. These marks on the trunk surface made the repeatability of the tests imperfect, as the initial conditions of the trunks were deteriorated test after test.
- The overhanging initial condition is probably more demanding than the real initial configuration of a harvesting head, where the fallen tree partially lays on its compressed crown. The results of these experiments at small scale should be carefully considered when transposed at full scale.

Despite some insufficiencies of the mono-functional feeding demonstrator, general properties can be extracted and summarized into the following conclusions:

- The rollers openings seems to be an important parameter for feeding performance. The optimal opening depends on the trunk properties.
- Feeding is successful when the plane of the crooked tree is horizontal, as expected by the professionals associated to the project. This can be explained by the lateral mobility of the gripping linkages that guide knives and rollers and can self-adapt to lateral deviations of the trunk centreline.
- The guidance length of a harvesting head, which is the distance between the plane of knives and the plane of rollers, affects enormously the head feeding performance. As a general rule, it exists an optimum between a too long distance, that will prevent feeding for crooked trees, and a too short distance, that will make the head sensitive to trunk overhanging and block the feeding because of excessive gripping forces.
- The existing concepts of harvesting heads can't overcome the problem of passing crooked trees, which makes the requirement for new designs more and more necessary. In these perspective, new architectures are being tested during this project and the first results are very encouraging.

5. Conclusion

This paper considered existing harvesting heads to evaluate their feeding ability on crooked trees, a major problem for the efficient mechanized exploitation of hardwood. The analysis of a harvesting head (Kesla 25RH) feeding behaviour and the subsequent 3D multibody models created with Adams software were not sufficient to fully comprehend the complex feeding phenomenon and to infer some design rules for better operation. The models were judged limited in some aspects and contact as well as dynamics parameters were not easy to identify.

With these limitations, a small scale demonstrator was manufactured, taking in account the scale effect with dimensionless numbers. This mono-fonctional demonstrator dedicated to the analysis of the feeding of crooked trees through the head allowed to make an extensive campaign of experiments and to study the influence of numerous parameters. The main conclusion is that parameters such as the rollers'opening and the guidance length have a critical effect on feeding. Moreover, the existing head designs fail to feed crooked crooked trees with anteroposterior curvature. With this last result, new concepts of innovative articulated heads dedicated to crooked trees are under development and the first results are very encouraging.

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