Serving Tray Revisited: A Novel Implementation of On Demand Bio-Inspired Attaching and Detaching

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***Abstract*—The content of this paper outlines the design process of an improved serving tray for glasses, focusing specifically on attaching and detaching on demand. A study was performed on the solutions found in nature, these were categorised using the ACCREx method, based on their working principles. From these solutions new concepts were derived and one was chosen to be finalised, which is based on the concept of a variable diameter. The prototype of the final design was validated to work under the specified conditions by conducting an experiment.**

***Index Terms*—bio-inspired, ACCREx method, serving tray, attaching, on demand, design, catering**

I. Introduction

It is a problem the catering industry has to deal with on a daily basis and even though this might not always be their fault, "Restaurants, bars, and hotels are taking the hit when it comes to broken glasses, spilled drinks, and cleaning bills", according to Foodnewsfeed [1]. A survey conducted by Foodnewsfeed revealed that one fourth of all employees in the hospitality industry "admitted they had burned or cut themselves while trying to serve drinks or food from a serving tray". The same survey showed that such accidents usually incurred a cost of more that $60. Almost half of the employees admitted that they had even ruined customers clothes with spilled drinks or food. Not to forget the overall unprofessional appearance towards the customers when such accidents happen.

As one can conclude, there is room for lots of improvement on the design of today's existing serving tray. In its current design, serving trays have no mechanism to increase stability of the glasses, or prevent them from tipping over. Despite the anti-slip coating of modern serving trays, each glass is balanced solely by the gravity on the glass itself and its contents. The catering industry could save money by investing in a serving tray that prevents glasses from falling, for example using the one presented in this paper.

This paper will focus on the solution of this balancing problem by utilising the principle of attaching and detaching on demand. In order to achieve the ultimate goal of preventing accidents and improving the design of the standard serving tray, the ACCREx method was used to come up with creative solutions in a structured way inspired by nature. The various stages of the design process will be presented in this paper.

First, a problem analysis is presented, which studies the real essence of the problem and suggest a way to solve this. From these conclusions, performance criteria are determined to create benchmarks for the novel solution. After that, various concept solutions will be discussed in detail by comparing their pros and cons, in addition to the justification behind the final concept selection. These sections provide a background on how the final concept was conceived, as well as a clear comparison between the various techniques discussed. After this, the final design will be presented along with a detailed performance analysis of this design. Finally, a conclusion can be found to summarise the major points outlined in this paper.

II. Problem analysis

The essence of the problem lies in the moments created by the forces acting on the relative high position of the centre of mass (COM) of a glass. Waiters walk with a tray and manoeuvre through often crowded places quickly when serving drinks. Due to these movements acceleration forces are exerted on these glasses by both the movement of the tray and the movement of the liquid in the glass.

The glasses are restricted from having a linear acceleration if the friction of the tray is high enough. Since this is true in most cases we do not focus on linear accelerations, but on the angular acceleration of the glass.

Since the COM of a glass is located at a distance from the bottom of the tray, as can be seen in Figure 1, a moment is created around the edge of the foot of the glass, point A. This moment causes the glass to tip over if it is larger than the counteracting moment caused by gravity. This counteracting moment of gravity gets a decreasing moment arm when the wineglass starts to tip around point A. When the COM is vertically aligned with point A the counteracting moment of gravity is zero (since the moment arm is zero). Beyond this point the moment created by gravity causes the wineglass to tip even faster.

Even if no acceleration forces are exerted on the wineglass, the wineglass can start tipping around point A. This happens when the tray is tilted with a certain angle such that the COM

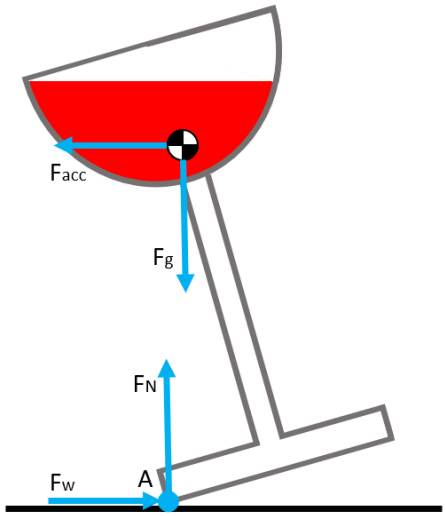


Fig. 1. Forces acting on a wineglass when it accelerates due to movement of the tray. The acceleration force generates a moment that causes the tipping motion. The gravitation force counteracts this motion until the COM is vertically aligned with point A. Beyond this point it causes the glass to tip over as well.

of the wineglass is on the left side of point A in figure 1. The moment that causes tipping increases with the height of the COM. The counteracting moment created by gravity increases with an increasing radius of the bottom of the glass. Since wineglasses often have a relative high COM and a relatively small foot (with respect to the height of the COM), these glasses are prone to tipping over, with all its consequences. The same holds for glasses that are tapered towards the bottom.

In this report a solution is presented that solves this problem by creating a counteracting moment to the tipping moment of the glass.

III. Performance criteria

In order to optimise performance and arrive at a practical and appealing solution, design requirements for the product were set. These design requirements can aid in narrowing down the solution space and specifying a general direction for the final solution. Such requirements have been derived from experiences of waiters, practical reasoning and literature. For the initial prototype, the requirements only include traits that must be met, hence will not include any optimisations or improvements. The requirements of the improved serving tray are categorised and outlined below, listed in general order of importance:

A) *Balance the glasses*
The design should be able to prevent glasses from tipping over under the following circumstances:

- When the tray is tilted up to 45 degrees with respect to the horizontal.
- When the tray is subjected to a linear acceleration of up to (-) 6.5 m/s.[2] [1]

B) *General Requirements*

- The mechanism should be driven manually.
- The design of the mechanism should be simple. This means that a prototype of the mechanism can be build within a week with limited resources. [2]
- The mechanism should be compatible with the glasses that are used in the catering business.
- The mechanism should not damage or dirty the glasses.

C) *Capacity*

- The tray should have a capacity of seven standard glasses.

D) *Ease of use*

- Only one action to fix or release a glass.
- Single handed action to fix or release a glass.
- A maximum time of approximately 1 second to attach or detach a glass.
- The mechanism holding the glasses should only be able to attach to the lower half of the glass.

E) *Dimensions*

- The maximum weight of the empty tray is 3 kg.[3]
- The diameter of the tray should be the same as that of a standard serving tray, which is 410 mm for the majority of trays.
- The maximum height of the tray is 50 mm.

F) *Durability*

- The tray should last for at least a year.
- The tray should be able to be cleaned relatively easily.

G) *Economics*

- The price of the entire tray should not be more than 30 euros.[4]

IV. Concepts

In this section three bio-inspired design concepts will be presented. These concepts were conceived using the ACCREx design method which will be discussed in this section.
As a first step, in order to explore all possible solutions available in this problem, a 2-D solution space was created as can be seen in figure 2, with different attachment positions against biological working principles which were found in nature for attaching and detaching. For the attachment position of the cup it was decided that there are three possibilities: bottom attachment, edge attachment and body attachment as shown in Figure 3. Biological solutions were found and categorised into the following working principles: suction,

[1]This number was found by measuring the maximum deceleration encountered when a person suddenly stops walking.

[2]Limited resources does in this sense mean that it can be build with materials that can easily be bought on the market. The building process of the design only requires tools or machines that can be found in a mechanical workshop, e.g. milling machines, simple 3d printers and laser cutters.

[3]This number is based on the average weight of a full serving tray of 6.3 kg [2]. Subtracting the weight of seven filled wine glasses, having a mass of 3.5 kg in total, leaves 2.8 kg for the tray.

[4]A professional serving tray with the same dimensions can be bought for 6 euros.

adhesion, friction and shape gripping. An attempt was made to find solutions for every element in the solution space. Only the three most promising concepts of these will be discussed.

After investigation and comparing different solutions, The

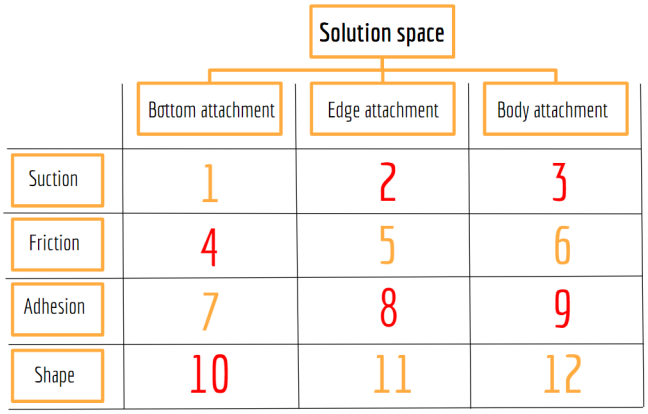


Fig. 2. The 2D solutions space used for the design process. For each of the combinations an attempt was made to come up with concepts. For the numbers indicated in orange this was done successfully.

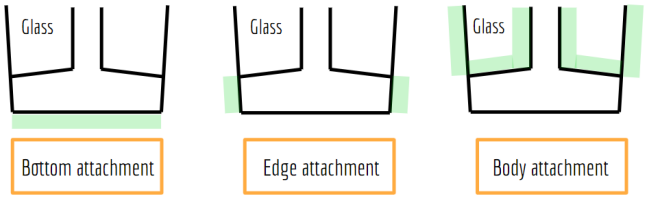


Fig. 3. The three different modes of attachment, bottom, edge and body respectively, that have been used to construct the solution space.

decision was made that the most realistic modes of attachment are body and edge attachment, using the working principles of shape gripping and friction. The three promising design concepts, based on these modes of attachments and working principles will be presented next, as well as the biological inspiration behind them.

A. Caterpillar Concept

The first design is inspired by the motion of the caterpillar, which can be seen in Figure 4. Caterpillars lift and compress their last segment, then move the last pair of legs forward a bit. This action is repeated in order for all other segments. A significant distance exists between the last pair of front legs and the first pair of the back legs (also called pro legs and true legs), so that the next step in the sequence is usually longer [3]. As shown in the Figure 4, the strips of rubbery material around the glass are able to creep up along it, just like the caterpillar's motion, following the shape of the glass. The concept uses a couple of these mechanism along the circumference of the glass in order to keep the glass in place. The motion of the caterpillar is driven by pulling the ends of the strips towards the centre of the glass. This is done by a wire that connects all of the ends and decreases in diameter when a force is applied to the wire. When this force reduced, the stiffness of the material will cause the strips to return to their original position. In the case of wine glasses, this concept only works if the base of the rubbery material where the force is applied is parallel to the surface of the tray. This ensures that pulling the strings will cause the rubber strip to shape around the foot of the glasses.

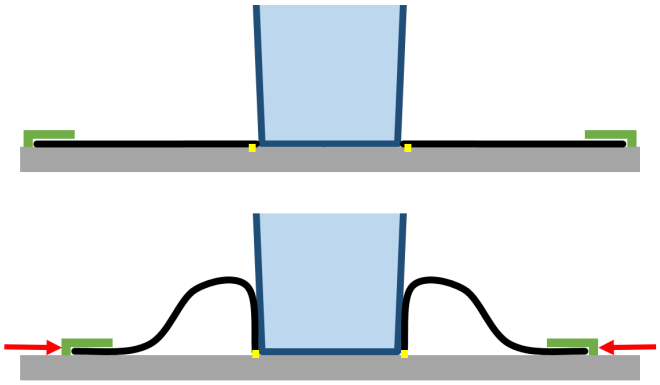


Fig. 4. Caterpillar concept [3].

B. Elastic Bands Concept

The second design was inspired by a spider's web, which acts as a trap in order to catch its prey. The high density network of sticky silk threads causes the insects passing by to be stuck to the web regardless of their shape.

The design consists of a network of radially aligned elastic rubber bands attached to the edges of the tray, as can be seen in Figure 5. The glasses are placed between these elastic rubber bands, which prevents them from falling. Wine glasses can easily be slid under the bands when held at an angle while being inserted. The bands will prevent the glasses from tipping over by holding the foot of the wine glass to the tray. In order to improve the stability of the glasses an inner concentric ring is added that also contains a network of elastic bands. This ring is rotated until the elastic bands are partially stretched around the glasses, after that the inner ring is locked with respect to the outer ring as shown in position 2 in Figure 5.

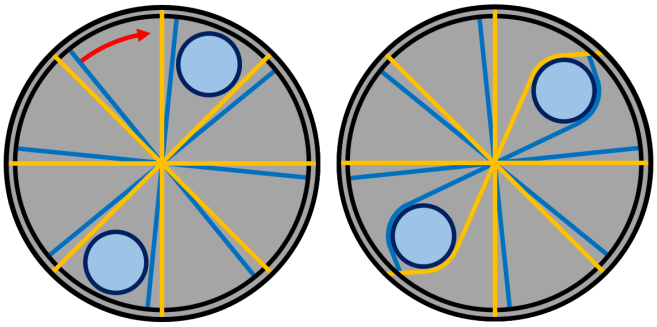


Fig. 5. Elastic bands concept.

C. Variable Diameter Concept

The third and final design is inspired by the the sphincter muscle action, which is a tissue present in animals and humans. It is a type of a circular muscle that controls the size of an orifice. There are over 60 types of these in the human body, some microscopically small [4]. Examples include the stomach, anus and the urinary tract. Also sphincter muscles are present in the human eye, changing the size of the pupil to control the entry of light. Another example of sphincter muscles in nature is the blow hole present on top of whales through which they breathe when they are above the surface of the water. The initial concept using the variable diameter principle was a mechanism using ropes and small pulleys that would loop around the glass from three sides, guided by small flexible tubes that would be retracted by springs once the diameter needed to open up again. The three sides guaranteed that the glass would be centred. Figure 6 illustrates how this idea worked.

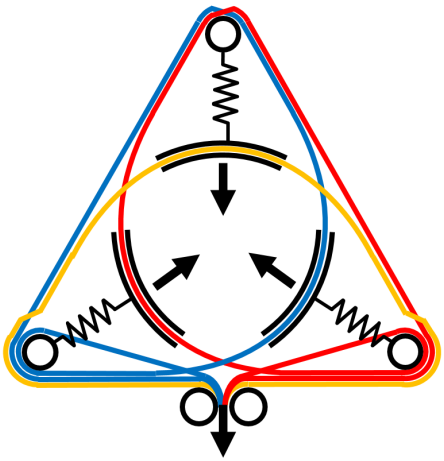


Fig. 6. Variable diameter concept.

V. Concept selection

To select the most promising concept for further development, the three concept solutions have been evaluated by assessing for each concept to which extent it meets the relevant performance criteria, and by comparing the performances of the concepts with one another. One thing all concepts have in common is that they are all capable of carrying both normal glasses and wine glasses. The criteria that will be used to compare the concepts are size, ease of use, clean-ability and gripping strength.

A. Size

First of all there is the size of the concept, which is important both for the ease of use as well as the amount of glasses that can be carried on a single standard sized tray. This is mostly a problem for the variable diameter and caterpillar concepts, which require the glasses to be in certain fixed positions in order to function. The elastic bands concept has an advantage here since the glasses can be placed in many different positions between the strings, which makes it possible to shift the glasses around slightly to make space for another glass. In contrast to this, the variable diameter and caterpillar concepts require a certain amount of space for the mechanisms around the glass, which means it will be harder to fit a large amount of these mechanisms on a tray. Furthermore, it will never be possible to have more glasses than mechanisms on a tray.

The variable diameter concept has another disadvantage when looking at the size of the concept. Since this concept works by gripping around the lower half of the glass, the concept has to be relatively high for it to be able to effectively counteract any moment working on a glass. This is especially the case when a comparison is made with the caterpillar concept, which works with edge attachment, and the elastic bands concept, where the elastic bands have to be just above the surface in order to effectively clamp wine glasses. This means that a tray that uses the variable diameter concept will have to be higher, and therefore bulkier, than a standard tray, making it less easy to handle.

B. Ease of Use

Another aspect of the concept that influences the ease of use is the amount of actions that are required to lock and unlock a glass standing on the tray. A concept can work in such a way that either all glasses are locked in place at once, or every single glass has to be locked individually, or a combination of the two. The elastic bands concept works by locking all of the glasses at once with the rotating ring, while both the variable diameter and caterpillar concepts can lock individual glasses, and both could also be modified to lock all glasses at once.

Locking all the glasses at once has the advantage of speed, but it also requires a larger force proportional to the amount of mechanisms. In the best case scenario of bringing seven glasses to one table, locking all glasses at once requires two actions, one lock at the bar and one unlock at the table. However, individual locking requires fourteen actions in that scenario, seven locks at the bar and seven unlocks at the table. In the worst case scenario of bringing seven glasses to seven tables, both concepts requires fourteen actions, since the concept locking all glasses at once requires all glasses to be unlocked and locked again if a single glass is removed. While this concept does make for faster serving the glasses will not be attached securely to the tray at all times, reintroducing the risk of glasses falling off. Furthermore, in the case of single locking it may be possible to add a way to either lock or unlock all of the glasses at once, combining the best aspects of both ways of locking.

C. Clean-ability

An important aspect of the concept solutions is the clean-ability of the entire tray. While all concepts should prevent the glasses from tipping over, there is still a chance of liquid splashing over the edge during a collision. This means that the effectiveness of the concept should not be impeded by a small amount of liquid, and that it should be easy to clean the tray.

The elastic bands concept will be the easiest to clean since the strings can be moved out of the way because of their elasticity. Another advantage is that the concept is modular because the rotating rings can be removed, which makes it possible to clean the individual parts. Of the other concepts the variable diameter concept will be the hardest one to clean, since it has a relatively large height and a large number of wires. The caterpillar concept uses edge attachment and does therefore not require a large amount of vertical space, which means there will be less hard-to-reach places on the tray.

The working principle of all the concepts is friction, and the caterpillar concept also uses shape grip for wine glasses. For this reason, all concepts use flexible or rubbery pads which provide a large friction coefficient on glass. This means that all concepts will be affected equally when the flexible pads get wet, but only when providing friction. Shape grip will probably not be affected very much since it does not depend on friction. This gives the caterpillar concept a slight advantage when carrying wine glasses.

D. Gripping Strength

All of the previous aspects of the design are important, but the most important design criterion does of course concern the gripping strength, or in other words, which concept can still keep the glasses in place under extreme conditions when the other concepts have already failed.

For the variable diameter and caterpillar concepts, the maximum gripping strength depends mostly on the force which is applied to the mechanisms, i.e. if the actuation force on the mechanism is larger the gripping strength increases. This is different for the elastic bands concept, since the maximum gripping strength in this concept is determined by the stiffness of the elastic bands and the extension of the bands caused by the diameter of the glass. This also reveals two conflicting wishes in this design: on the one hand the elastic bands have to be moved apart to put a glass between them, which means the bands should have a low stiffness to prevent people from spilling drinks while trying to insert a glass. On the other hand, the bands should have a very high stiffness since that will lead to a larger stabilising force being exerted on a glass.

The locking mechanism somewhat alleviates this problem by allowing the bands to be spaced farther apart. This is the case because the locking action causes the bands to wrap tighter around the glass, thereby increasing the normal and friction force. As a result the bands can be a little farther apart in their unlocked position while still having the same stiffness, which makes it easier to insert glasses. This problem does not appear at all for the other two concepts which have clearly defined ‘open’ and ‘closed’ states, meaning that the insertion of the glass is not being counteracted by the stabilising force.

The problem mentioned above raised some questions about the performance of the elastic bands concept, and for that reason a small prototype was built in order to qualitatively analyse the performance of the concept [Fig. 7]. This prototype showed that the concept was capable of attaching glasses to the tray, but it also revealed a few problems. First of all



Fig. 7. Simple prototype of the elastic bands concept.

there is the problem of counteracting moments that work on the glass when the tray is tilted. Because the point of contact between the glass and the bands was at a low height of only a few millimetres, the prototype had some trouble counteracting these moments. This is also connected with the second problem, which is that the glass was especially prone to tipping over when the tray was subjected to large accelerations or shocks. This problem is caused by the stiffness of the elastic bands, which cannot be very stiff for reasons named in the previous paragraph. Because of this, the inertia of a heavy glass filled with liquid makes that it can still move when it is subjected large accelerations even though the elastic bands are trying to keep it in place. This is a serious disadvantage of the elastic bands concept, and while the tipping over could be reduced by elastic bands with a higher stiffness (which will make the concept less easy to use), the oscillations of the glass when subjected to large accelerations are inherent to the concept.

Just like the elastic bands concept, the caterpillar concept would most likely have some difficulty with counteracting moments as well. Since the concept uses edge attachment the height difference between the point where the strips forming the caterpillars touch the glass, and the COM of the glass, will be large. While the caterpillar strips themselves are flexible, the strings connected to these strips are not, which means that any accelerations of the glass are absorbed by these non-elastic strings. This means that a glass attached with this concept, unlike the elastic bands concept, will not be able to move when it is accelerated. As a result the caterpillar concept should perform better than the elastic bands concept under linear shocks and accelerations, but it will probably have just as much trouble with large moments.e

When compared with the other two concepts the variable diameter concept is a lot more stiff, and will probably have the largest gripping strength. This is caused by the lack of flexible elements, with only the pads touching the glass being somewhat rubbery to increase the amount of friction that can be provided. Since that point of contact between the mechanism and the glass is also much closer to the COM than it was for the other concepts, the variable diameter concept will

have no problem counteracting the moment caused by a tilted glass.

In the end it was decided to continue development on the variable diameter concept. This concept is able to provide the stabilising force close to the COM, and is therefore well suited for counteracting moments caused by the tilt of the tray. This concept is also more stiff than the other concepts, which makes it the best concept for keeping glasses fixed in place. However, this good gripping strength does come at a price. The variable diameter concept has a larger height than the other two designs, increasing its bulk and making it less easy to use. This also decreases the clean-ability by creating more hard to reach places. With everything taken into consideration it was eventually decided that the gripping strength was the most important aspect of the design, and that it would be easier to improve the usability than the force characteristics. For this reason the strings and caterpillar concepts were discarded.

VI. Final Design

From the chosen design concept, Figure 6, the variable diameter, a two-layered design was realised. The idea was that there would be two parallel plates, one just being the serving tray itself, the plate where the glasses would rest on. The second plate would be raised a few centimetres above the bottom plate, and this plate would have holes in which the glasses should be placed. In between the two plates would be built a mechanism to close the diameter of the holes. Of great importance was that this mechanism should close the hole symmetrically around the glass, so that glasses would be centred in the hole.

Different ways of closing this hole were considered. One of them was a shutter of a camera, that consists of multiple small plates that slide along each other in a circular motion, and because of the nature of the shape of these pieces, the opening would be closed symmetrically. It seemed very complex however with many moving parts, and prone to friction. See Figure 8 for an overview of a possible setup for such a system.

We then looked at curved flexible structures, sticking out from underneath the upper tray into the holes in which the glasses should go. These arched bands, when designed in a way that they all pointed towards the middle of the circle, could create a variable diameter by bringing together the ends of these flexible semicircles, see Figure 9. Due to the deformation, the shape of the curves would change and the curves would adapt to the surface of the glass, having a shape sticking inwards further into the holes.

Due to the flexible nature however, the thickness of these rubber bands was of great importance: having too thin of a band would not create enough surface to keep the glass down. Having too wide of a band would however prevent the system from being actuated easily, due to the stiffness of the rubber. Some rethinking and looking at the design from different angles quite literally, resulted in the idea of using the rubber bands vertically, instead of horizontally, attaching them to the upper plate and the lower plate basically, as

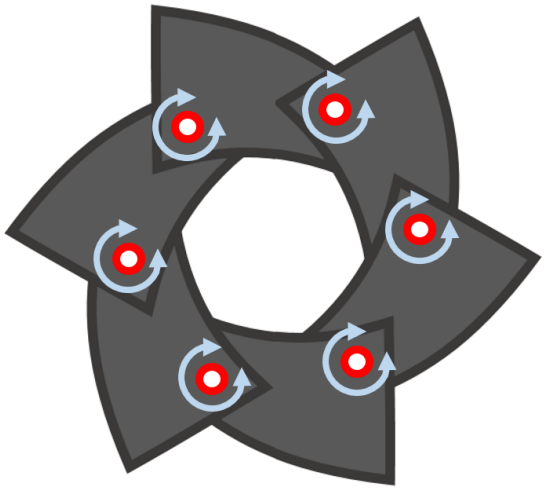


Fig. 8. The aperture configuration to realise a variable diameter.

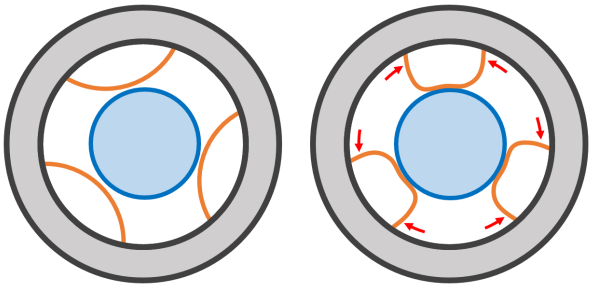


Fig. 9. The horizontal flexible curves concept in detached and attached configuration. The orange bands follow the shape of the glass when the ends of each band are brought closer together.

depicted in Figure 10. When now the distance between the plates was reduced, the bands would also want to protrude inwards, reducing the diameter. This idea formed the basis for the final concept.

First of all a prototype was made, which showed that just lowering the top plate was not enough. When next to lowering the plate, the plate was also rotated axially with respect to the centre of the hole, the outward buckling motion that the flexible bands encountered when trying to hold larger glasses was counteracted. The combination of reducing the distance between the ends of the rubber bands and also rotating them, proved to be very effective. With this motion also wineglasses could be held in position very effectively due to the bands actively pushing down on the foot of the wine glass. A consequence of this whole mechanism was that the glasses would have to be attached individually, because the amount of distance that the plate should go down in order to reduce the diameter was different for differently-sized glasses.

The prototype worked as follows: two round metal plates were created, one having a 120mm hole in its centre, and they were spaced 50mm apart by a cylinder having also an inner

diameter of 120mm, this is the red part in figures Figure 10 and Figure 11. Six rubber bands were attached to the bottom plate, their curvature pointing inwards. On top of these bands, a ring was attached that could move freely within the 120mm cylinder, but had an inner diameter of 80mm, a size in which most standard glasses fit. This ring is depicted as the green part in Figure 10. This ring acted as the plate that could be manually lowered and rotated to create the desired effect in the rubber bands in order to clamp the glass that should be placed inside this ring. The design however had a mechanism that coupled the lowering motion to the rotating motion by means of three diagonal slots (Figure 11) in the 120mm cylinder, and three pins attached to the movable ring that were confined to these slots.

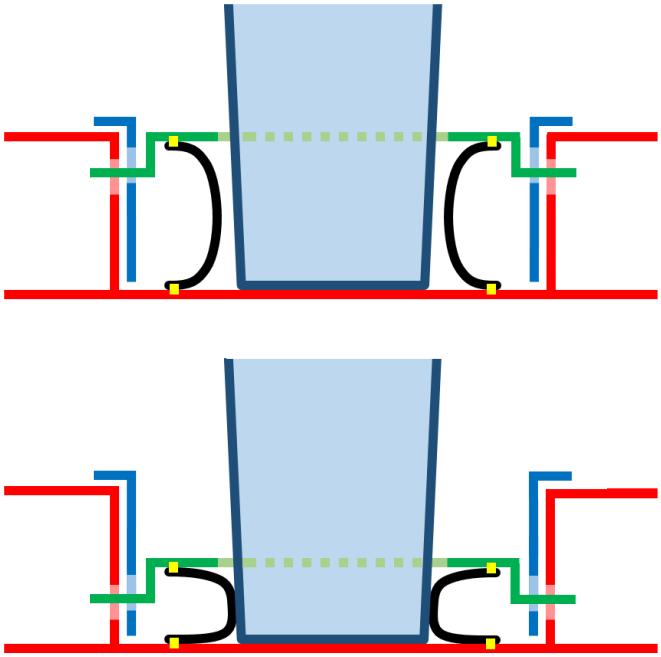


Fig. 10. Variable diameter concept, in detached configuration and in an attached configuration.

Moreover, these three pins were connected with wires to three springs that pulled them back up through the slot to the highest position, so that the movable ring would be at rest in the highest position and the rubber bands would open up the hole. These slots however were also part of the locking mechanism, that consists of small gaps in the upper side of the slots, so that the three pins would get stuck in one of these gaps instead of just being pulled back up when the movable ring was pushed down and released. Together with the stiffness of the rubber bands this mechanism worked quite well, however there was no easy way to unlock the system again. To achieve this, another cylinder with corresponding slots was placed in the 120mm cylinder, but this new cylinder was still on the outside of the movable ring, so that the pins would have to go through both cylinders now. This pushable ring is depicted in Figure 10 and Figure 11 with a blue color. This new ring however had no gaps in the slots, so no locking could be provided with this cylinder. This new cylinder was also locked from rotating in the larger cylinder, but could still move up and down a bit since the slots around the pins were a bit wider than the slots in the larger cylinder. When this movable cylinder was in its upper position, the gaps in the slots in the outer cylinder were free for the pins to enter: the system could be locked. When this inner cylinder was pushed to its lower position however, the pins would slide along the edge of the inner slot that now covered the gaps in the outer slot, so that the springs could once again pull the pins back up to their highest position. This inner cylinder worked as an unlocking mechanism in this way, and when a few springs were added to keep it in its highest position when at rest, the prototype fully functioned. Now, the glass could be put in, the movable ring could be pushed down, it would automatically rotate and lock, and when the glass had to be served one could just push the inner cylinder (having a convenient little flange on top for ergonomics), and the system would spring back into its open configuration.

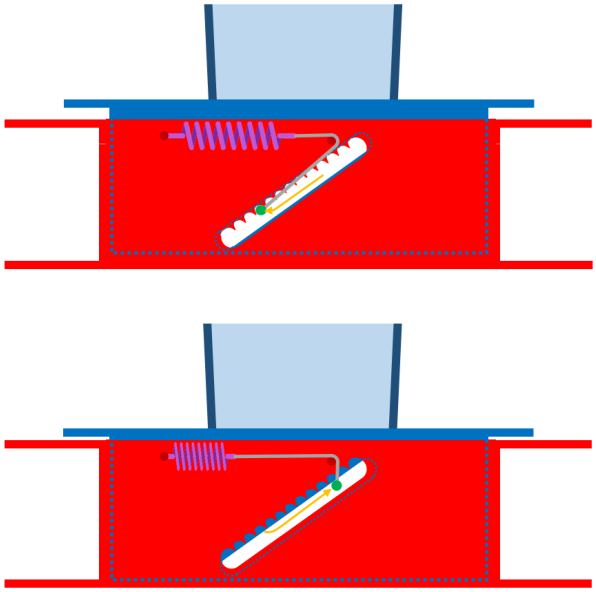
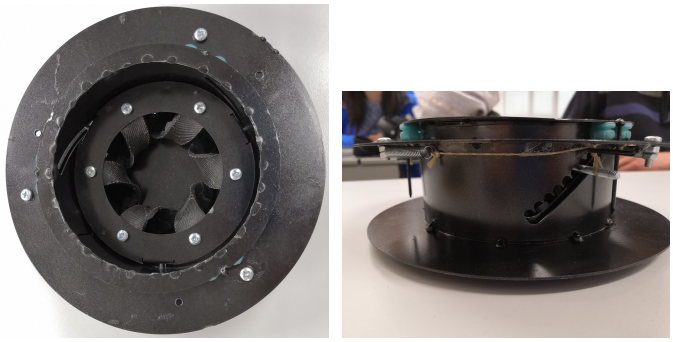


Fig. 11. The locking mechanism. The dotted lines indicate the shape of the blue pushable part, that unlocks the green pin from the gaps.

In short: the final concepts uses bendable rubber bands that hold the glass when a ring is pushed downwards (also rotating it to prevent outwards buckling). When the ring is released, it locks. By pushing another flange, the locking mechanism can be released again, and the ring will pop up and rotate back, unlocking the glass.

VII. Performance analysis

In this section the performance of the improved serving tray will be analysed based on the criteria that were set. This analysis is done using the prototype that was made, as presented in Figure 12. In some cases the performance will be assessed based on an estimated performance of a more optimal version of the design. We start off the analysis by assessing ease of use of the improved serving tray.



(a) Top view (b) Side view

Fig. 12. Realisation of the prototype for the final design

In the final design the glasses can be locked and released with one single handed action. However locking a glass with one hand using the prototype can sometimes be hard due to the force required. Due to this, it also takes more than 1 second to lock the glass. This is caused by the sub-optimal design of the prototype. With some optimisation of the components, this design will have a smoother motion. An example of this is the guiding mechanism guiding the twist-down motion. In the prototype this is done by sliding contacts between two steel parts. Changing the material of the ring that guides the steel rod to plastic would result in a lower force required for the locking action. Using rolling contacts instead of sliding contacts could further reduce the required force.

The gripping mechanisms of the tray do not satisfy the requirement that it should be relatively easy to clean the mechanism. This is an important issue for the catering industry, since there are strict rules in this industry involving hygiene. This issue also affects the requirement that the mechanism should not dirty the glasses. If the rubber bands are hard to clean after some fluid is spilled on them, they will dirty the glasses. This issue can be solved by making the design modular, such that each component can be cleaned by a standard dishwasher.

In order to test the working principle of the prototype, the gripping strength is measured using different glasses which are commonly used in the catering industry. The glasses are shown in Figure 13 and numbered 1 to 4 for ease of use.



Fig. 13. Commonly used glasses in the catering industry

The weight of the prototype is 0,775 kg. This is too heavy considering that seven of these mechanisms need to be placed on a tray, resulting in a added weight of 5,43 kg to a tray. However, for the ease of producing the prototype it was mainly build out of steel. Besides that the prototype was over-engineered, since the focus was on displaying functionality. When the mechanism is mainly build out of plastics and produced using 3D printing or moulding with a more optimal design, this weight can be reduced to a total weight per mechanism of 150 grams. With seven of these mechanisms on a tray this would result in a weight of the empty tray of about 1 to 1.5 kg. This satisfies the weight requirement that was set earlier. [5]

The size of each mechanism could also be decreased by optimising the design. With the current dimensions of the mechanism, it fits seven times on a standard serving tray with a diameter of 410 mm, resulting in a capacity of seven glasses. Decreasing the dimension of the mechanism would make the design less bulky and could also increase the capacity of the serving tray. The height of the design is 50 mm, which is just within the boundaries that were set. This height cannot be reduced significantly without loss of performance in the current configuration, since the system works by converting a change of height into a change of the diameter.

A. *Gripping strength experiment*

Two cases have been studied, the tipping over of a wine glass shown in 14a and the tipping over of a standard size glass, as shown in 14b. The former has a higher total weight and the latter has a higher centre of mass (see second column in Table II).

When a glass has a diameter smaller than the minimal diameter the mechanism can reach (40mm), the glass can only be locked if it has a foot larger than 40mm. The attaching mechanisms are visualised as a rigid band in Figure 14. The attaching mechanism of the normal glass is based on the principle of friction, while the wine glass is held in place using shape gripping.

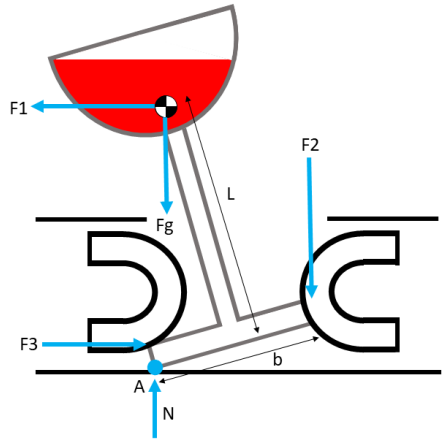
As already mentioned before, the deceleration of a waiter is measured, for a full or sudden stop when walking. This can later be used to calculate the forces acting on the glasses due to the moment of inertia. With this information, the required counter forces can be determined, to prevent the glasses from falling.

Once the data is obtained, the required counter moments can be calculated and plotted. After that, a conclusion can be drawn about whether the prototype is capable of stabilising the glasses or not.

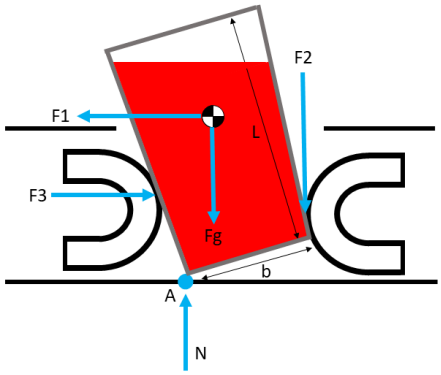
B. *Results*

The results of the deceleration tests (three in total) are shown in the appendix, in Figure 17. The average deceleration of the waiter is approximately -5.6m/s^2 and the maximum deceleration is about -6.6m/s^2.

[5]This weight was estimated based on a model build in SolidWorks, a 3D CAD program.



(a) Case study wine glass (shape gripping and friction)



(b) Case study normal glass (friction)

Fig. 14. Glasses categorised, for clarity only the relevant forces are shown

Next, the vertical gripping strength for different glasses was measured. This was done for wet and dry conditions. The results for three consecutive tests are shown in Table I.

TABLE I
RAW DATA GRIPPING STRENGTH TEST IN GRAMS

Glass 1		Glass 2		Glass 2		Glass 2	
Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
>5000	>5000	1625	2000	1250	1500	1250	1175
>5000	>5000	1625	1875	1500	1500	1250	1375
>5000	>5000	1750	2150	1300	1375	1300	1375

C. Discussion

The data obtained from the experiments can now be used to calculate the clamping forces, using $M = F \cdot r$. Hereby, Figure 14 is taken as a reference for the situation. The results can be seen in Table II. The gripping strength is slightly dependent on the diameter of the standard glasses. The gripping strength for the wine glasses is very high, due to the shape gripping principle. Interestingly, the gripping strength for all glasses increased significantly when the tray was wet, which is often the case in the catering industry. This might be caused by the mesh-like structure present in the rubber bands used. The rubber bands used were bicycle tires, of which the inside was used as contact area with the glass.

TABLE II
AVERAGE GRIPPING STRENGTH IN NEWTONS (SIGNIFICANCE LEVEL 95%)

Glass	Net weight [N]	Diameter [mm]	Grip strength [N]	
			Dry	Wet
1	2.45	10 [6]	>49.1	>49.1
2	3.68	70	16.4±0.7	19.7±1.4
3	2.70	60	16.6±1.3	19.7±0.7
4	2.45	55	17.2±0.3	21.1±1.1

The required moments as a function of the tipping angle θ of the tray and glass are shown in Figure 15. The moments correspond to the forces indicated in Figure 14. F_1 is the force created by the inertia of the wineglass during a deceleration. F_2 is the stabilising force created by the rubber bands. M_2 is equal to the sum of the moments M_1 and M_g around point A. There is a maximum moment to be countered, at an inclination of $\theta = 60°$. This moment is about 0.6Nm for a wine glass and 0.45Nm for a standard size glass. M_{max} is the maximum moment that can be countered using the prototype. This maximum is calculated using the data obtained from the gripping strength experiment. The maximum for a wineglass is 1.7Nm and for a standard glass about 0.6Nm, which is significantly lower. However, the prototype is in both cases able to stabilise the glasses with the maximum deceleration, because the maximum moment due to this deceleration is smaller than the maximum calculated counter moment.

TABLE III
TOTAL COST FINAL PROTOTYPE

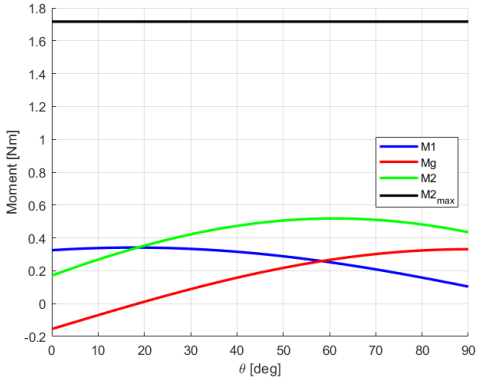
Item	Price [€]
Springs	1.04
Finishing	3.00
Bolts & nuts	3.50
Steel	4.81
Laser Cutting (30min)	12.60
Total	24.95

The total cost of the prototype is shown in Table III. This is less than the maximum cost of €30 that was specified in the performance criteria, and with mass production the material costs can be reduced further still. The laser cutting is responsible for more than half of the total cost, but this will of course change if the final design is produced with methods such as 3D printing or moulding.

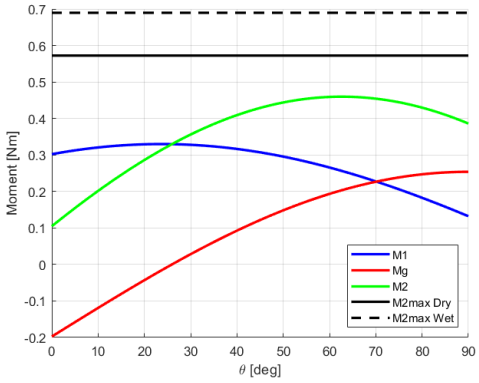
VIII. CONCLUSION

The objective of this project was to design an improved version of a standard serving tray, in order to make it impossible

[6]Because 10mm is smaller than the minimum reachable diameter of 40mm, this results was achieved with shape grip on the top of the foot of the glass.



(a) Situation of the standard wine glass, where M_1 is the moment due to inertia, M_2 the counter moment created by the rubber bands and M_g the moment due to gravity. $M2_{max}$ is the maximum moment that can be created by the prototype



(b) Situation of the standard glass, where M_1 is the moment due to inertia, M_2 the counter moment created by the rubber bands and M_g the moment due to gravity. $M_{2,max}$ is the maximum moment that can be created by the prototype – in the case where the prototype is wet and where it is dry

Fig. 15. Moments in Nm of categorised glasses

for glasses to fall off the tray while it is being carried. This means that the problem was one of attaching an object to a surface in a reversible manner. A key part of the design process was examining the ways in which nature has solved similar problems, by looking at the functioning and anatomy of both plants and animals. This provided inspiration for designing the concept solutions, leading to a design that is based on the sphincter muscle and that uses a combination of friction and shape grip to constrain movement of the glasses. A working prototype of this design has been made that meets most of the performance criteria, and that can be modified relatively easily in order to meet the other criteria. Therefore the prototype has proven the feasibility of the design and of the method of attachment.

The final design is capable of carrying and stabilising both wine glasses as well as normal glasses, with diameters of up to 80mm. In order to do this the design uses shape grip when gripping a wine glass, and friction when gripping normal glasses. During the performance tests this led to a vertical gripping strength in both wet and dry conditions of more than 49N for wine glasses, and of at least 16N for normal glasses. This means that a glass filled with fluid can be kept in place by the mechanism even when the tray is rotated 180 degrees, since the heaviest (empty) glass in the test weighed just 3.68N. While the fluid will have fallen out of the glass at this point, this does show that mechanism will be able to keep the glass in place under all static rotations. It was also shown that the glasses are stabilised under a linear deceleration of up to 6.5 m/s^2, which is the experimentally determined deceleration experienced by the glasses when a waiter carrying a tray comes to a sudden full stop.

Since the attachment mechanisms with the rubber bands work independently for every single glass, glasses of variable diameters can be carried at the same time. This also means that the design is modular, and trays of different sizes can be designed easily by adding or removing mechanisms. While the mechanism does take up more space on a tray than a single glass, it is still possible to fit enough mechanisms on a tray to carry seven glasses at once. Since the current prototype is made out of steel this would make for a heavy tray, but if the design is made from plastic using 3D printing or moulding instead, the total weight of the tray could be reduced drastically.

Furthermore, the design is very easy to use and requires only one action to lock or unlock a glass. These actions are controlled by two separate rings which only have to be pushed down, an action that can be performed with a single hand. While this action still requires a relatively large amount of force in the current prototype, the design can be improved to reduce the amount of force needed. This can for example be done by replacing the sliding contacts by rolling contacts. If these optimisations are carried out it is not necessary to put the tray on a table in order to remove a glass, instead a waiter can hold the tray with one hand and remove glasses with the other hand, just like a standard tray. This also means that the workflow of a waiter is not impacted negatively, since the (un)locking action does not take much time when the mechanism moves smoothly. A maximum (un)locking time of 1 second as was specified in the performance criteria should therefore be attainable.

Next, the design is hygienic and will not damage or dirty the glasses. Since only the lower half of the glass is used in order to keep it in place, the area used for drinking will not be touched by the mechanism and will remain clean. Also, the rubber bands that are used to stabilise the glasses will provide a large gripping force in both wet and dry conditions and will not scratch the glasses. The clean-ability of the tray is still lacking since there are some hard-to-reach areas inside the mechanisms, which could be solved for example by introducing modularity in the design. This way it may be possible to separate the design into several components that can be cleaned easily.

Finally, the prototype had a total cost of €24.95, which is not a price that is commercially feasible. However, this does show that the cost for one hand-made mechanism is not

exorbitantly high, which means it should be possible to reduce the cost by using mass production and more cost-efficient manufacturing methods.

If all of the recommendations that have been mentioned are carried out, the result will be a modular and relatively lightweight mechanism that is well suited for fixing glasses to a serving tray. Furthermore, since the design is based on the concept of a variable diameter, there are also possibilities for gripping other cylindrical objects. Instead of using the mechanism to fix glasses to a tray, the gripper could be attached to a wall or a (low) ceiling to function as a novel storage solution for glasses. This would work well for restaurants where the design would combine form and function resulting in an interesting and novel alternative to normal shelves. Another potential application can be found in pick and place where the design could be used to pick up cans or bottles. Further research would be required to determine the advantages of using this method over the methods that are currently being used in the industry.

All in all it can be concluded that the method of attachment that has been designed can effectively fix glasses to a tray, and that it also has potential for other applications.

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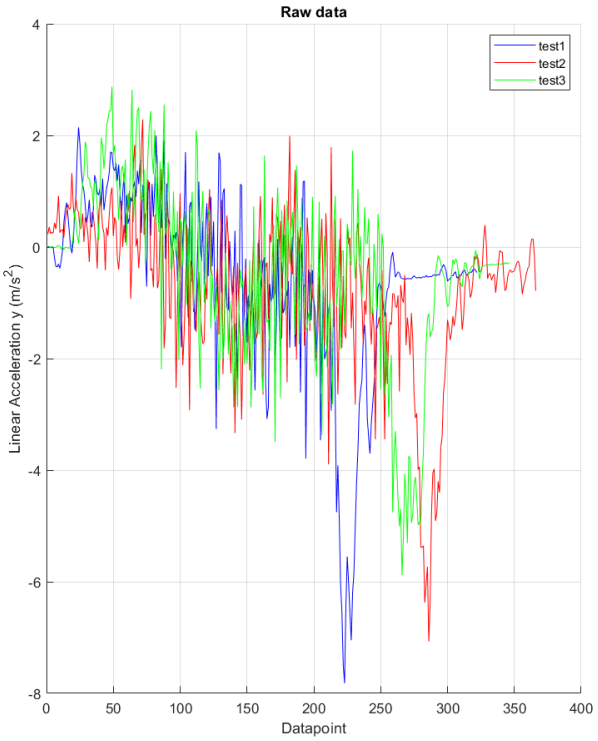
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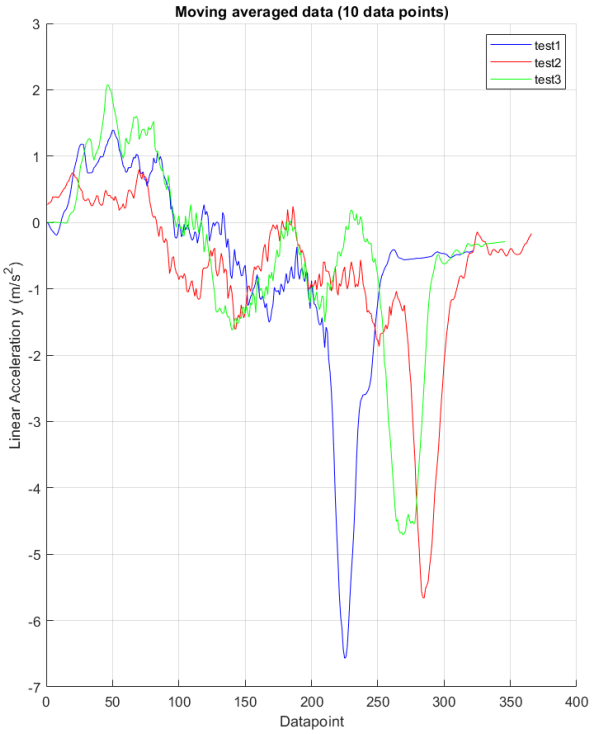
APPENDIX A
FIGURES



Fig. 16. Setup experiment gripping strength



(a) Raw data



(b) Filtered data using a moving average

Fig. 17. Deceleration profile sudden stop waiter