A Platform for Dance Performances with Multiple Quadrocopters

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***Abstract*— This paper presents a platform for rhythmic flight with multiple quadrocopters. We envision an expressive multimedia dance performance that is automatically composed and controlled, given a random piece of music. Results in this paper prove the feasibility of audio-motion synchronization when precisely timing the side-to-side motion of a quadrocopter to the beat of the music. An illustration of the indoor flight space and the vehicles shows the characteristics and capabilities of the experimental setup. Prospective features of the platform are outlined and key challenges are emphasized. The paper concludes with a proof-of-concept demonstration showing three vehicles synchronizing their side-to-side motion to the music beat. Moreover, a dance performance to a remix of the sound track 'Pirates of the Caribbean' gives a first impression of the novel musical experience. Future steps include an appropriate multiscale music analysis and the development of algorithms for the automated generation of choreography based on a database of motion primitives.**

I. INTRODUCTION

The interface of music and robotics has become a prominent area of research, attracting the attention of not only roboticists, but also musicians, artists, and the general public. When robot technology is brought together with musical expression and rhythmic performance, it opens up the space for a novel human-robot interplay and a unique musical experience that cannot be achieved by traditional means.

During the past decade research on musical robots has, for the most part, been driven by two distinct communities.

The first – consisting mostly of musicians, composers and music technologists – has generally sought to develop innovative forms of musical expression and sound production that overcome the limitations of human music generation and traditional musical instruments. Early robotic developments from this first community include the automation and mechanization of instruments, such as the piano, percussion and woodwinds (see [1], [2] and, for a historical overview, [3]); more recently, this group has been behind the development of perceptual music robots [4], some of which facilitate music collaboration with human musicians [5]–[7].

The second community, working out of the fields of robotics and engineering, has sought to use music to establish a new dimension of human-robot communication, interaction and collaboration. Research from this second community has been largely focused on the development of humanoid robots capable of imitating human musical behavior: robots that perform human-inspired rhythmic motions, such as dancing [8]–[13], drumming [14], stepping and singing [15]–[17] along to music. Common to both communities is the desire to create an audio-visual performance with both aesthetic and entertainment value; this merging of musical expression, robotic technology and entertainment has also been a fascinating playground for artists [18], [19].

The goal of this work is to create a novel visual musical experience: Multiple quadrocopters fly in a rhythmic performance, expressing the character of the music as they move in a coordinated and precisely-timed fashion through the three-dimensional space. Prior to flight performance, a random piece of music is analyzed and its main features are extracted. These features are later used to guide the quadrocopters' choreography. This approach differs from most other research on musical robots, which typically aims for a real-time interaction with the environment and which studies the problem of real-time music analysis, see e.g. [5], [17], [20]–[23]. In contrast, the focus of this work is the design, control, and synchronization of the rhythmic quadrocopter motion. Major challenges include:

Motion Design – Given the body and dynamics of a quadrocopter, translating music into suitable motion patterns is a significant artistic challenge. Unlike humanoid dance robots, which may imitate any human dance movement and produce an easily-recognized expressive gesture [8]–[13], quadrocopters do not move the way humans do. Choreography of their movement is new, and requires creativity, aesthetic judgment and a deep understanding of the system's dynamics and its limits.

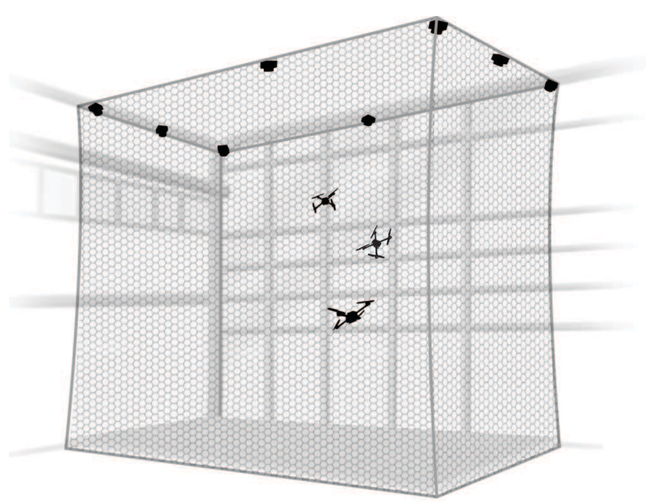

Fig. 1. The Flying Machine Arena, an indoor flight space for multiple quadrocopters.

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Associated video at www.tinyurl.com/DancePlatform.

Motion Control – A quadrocopter's nonlinear and unstable dynamics, cf. [24], demands sophisticated controls in order to achieve precise trajectories and exact audio-motion synchronization. Modeling errors and other nonidealities, such as motor saturation and communication delays, have a noticeable effect on the quadrocopter performance. Note that a stabilizing controller is required just to keep the vehicle in the air. Moreover, additional underlying controllers impose a periodic oscillation corresponding to the music frequency, presenting the basis for an overall rhythmic behavior.

Motion Synchronization – To make the quadrocopters 'dance to music', it is essential to time the vehicle movement with the music beat precisely. In the proposed setup, however, the quadrocopters' dynamics are highly non-linear and not fully identified. Furthermore, the system's time delays are variable. An appropriate synchronization algorithm is therefore indispensable. Note that in most other approaches on musical robots, simple adjustments (like a constant time shift of the reference signal) are sufficient for synchronization, since they deal with systems that are better understood, less sensitive to disturbances, and, generally, easier to manage, see [9], [10], [15], [22], [25]. Inspiring work that explicitly considers synchronization is presented in [14], [16], [23], [26].

Motion Composition – Given an arbitrary piece of music, music analysis extracts the associated sequence of music features with the corresponding timing information. The goal is to automatically generate a dance performance with multiple quadrocopters, where the quadrocopters' motion not only reflects the character of the music but also takes into account the physical limitations of the space and the vehicle. We plan to develop an automated tool that will compose a suitable multi-vehicle choreography based on a selection of motion primitives (see *Motion Design*). Previous work on automatic music-driven dance synthesis focused exclusively on human dance motions; music features were analyzed and mapped manually to real human dance movements, cf. [27]–[29]. Algorithms were visualized and tested solely in virtual environments.

The core components mentioned above build upon a prior music analysis that extracts important music features, such as beat, dynamic range, pitch, melody, etc., together with their timing information. The success of this project depends heavily on the quality of the multiscale music analysis. Various algorithms and software solutions (see [30], [31]) are available, especially for tempo and beat analysis, among others [32]–[36]. Moreover, every year researchers present the latest music analysis solutions at the Music Information Retrieval Evaluation eXchange (MIREX). In collaboration with those music experts, we would like to ask the following questions: Which music features are critical to the development of a musical quadrocopter performance? And which algorithms fit the proposed application?

This project aims to combine musical expertise, emotion, and aesthetic judgment with agile aerobatic maneuvers and sophisticated control techniques. In this interdisciplinary context, collaboration with a variety of experts is essential.

Fig. 2. The quadrocopter, measuring 53 cm in diameter.

The objectives and prospective features of the proposed platform are presented in Section IV together with a proof-of-concept demonstration in Section V. The associated video, available also at `http://tinyurl.com/DancePlatform`, provides a first impression of the intended quadrocopter flight dance. The experimental setup and the characteristics of the vehicles are described in Section II, and Section III explains the synchronization problem encountered when working within the proposed environment.

II. Experimental Setup

It was the agility of the quadrocopters, the dimension of the flight space, and the reliability of the communication and control infrastructure that laid the foundation for a musical dance performance with multiple vehicles. In the following, we sketch the experimental setup in order to convey an impression of the project's starting conditions.

A. The Flying Vehicle

Figure 2 shows the current flying vehicle. The quadrocopter is characterized by its small size, light weight, and structural and electronic robustness, making it a versatile and easy-to-operate experimental platform. The baseline platform is a X3D 'Hummingbird' quadrocopter designed and manufactured by Ascending Technologies GmbH [37]. Measuring 53 cm in diameter, the vehicle's overall weight including the onboard battery is approximately 460 g. The operational flying time varies between 10 and 20 minutes depending on the aggressiveness of the performed flight maneuvers. The vehicle is equipped with four brushless DC motors, which together are able to produce a vertical acceleration of around 12.5 m/s.

Though the original propulsion system, the motor controllers and the frame of the standard X3D quadrocopter were preserved, cf. [38], the central electronics and onboard sensors were replaced to obtain better control over the onboard algorithms and to have access to better-quality and higher-range rate gyro data. These changes allow for more aggressive maneuvers, faster turn rates, and generally better flight performance. With the new rate gyros, rotations of up to 2000 deg/s are possible around the body's principal axes of inertia. Detailed documentation of the changes are found in [39].

The quadrotor accepts three body angle rate commands and a collective thrust command at 50 Hz. An onboard 800 Hz feedback controller uses rate gyros to track the given commands. The exact onboard controller design is presented in [39]. Propeller wear trim factors allow for precise balancing of the quadrocopter. Each vehicle is equipped with two radio systems: a one-way 2.4 GHz module used exclusively for controlling the vehicle (to constrain the amount of variable latency in the system), and a bidirectional 2.4 GHz transceiver with a different modulation for non-time-critical communication such as data feedback or onboard parameter reads/writes.

Each quadrocopter is also equipped with three retro-reflective ball-shaped markers, which enable unambiguous vehicle identification by the Vicon communication system (described in Section II-B and II-C) during flight.

Currently, six vehicles are ready to fly.

B. The Space

A $10 \times 10 \times 10$ m cube of indoor space, called the ETH Flying Machine Arena (FMA), is reserved for testing and validating autonomous quadrocopter flight, see Fig. 1. For a safe operation, the space is equipped with protective nets delimiting the space on three sides. A glass front on the fourth side allows visitors an undisturbed view of the flying vehicles. To reduce the occurrence of catastrophic crashes, 12 cm thick foam mattresses cover the ground. An 8-camera Vicon motion capture system [40] provides position and attitude data for all appropriately marked vehicles in the arena at 200 Hz with millimeter accuracy, and a latency of about 10 ms.

C. Control and Communication

The overall organization of the system is similar to [41]. The localization data provided by the Vicon system is sent to off-the-shelf PCs, which then execute estimation and control algorithms. These in turn deliver commands to the quadrocopters with an approximated latency of 20 ms. The overall system time delay, from sending a vehicle command to detecting the corresponding effects in the vehicle's Vicon pose data, varies between 10 ms and 40 ms with a mean value of 35 ms.

Data is sent via a multicast UDP scheme, allowing for convenient online visualization of all data sent over the network, and also for recording, playback, and export of arbitrary customized data series. A convenient side-effect of this setup is that estimation and control components are binary-identical when running in the real system or in simulation. The wireless and Vicon data bridges are simply replaced by a simulator process, with all of the other components remaining completely unaffected and unaware of any difference.

During normal operation the vehicle's translational degrees of freedom are controlled by linear PID controllers designed for near-hover operation. Yaw is held at a constant angle via a proportional controller. To achieve trajectory tracking, a sequence of reference points are fed to the controller together with appropriate feedforward commands. More details about this test environment may be found in [42] and [39].

Fig. 3. The desired side-to-side motion, a schematic of the two-dimensional quadrocopter model.

III. THE SYNCHRONIZATION PROBLEM

Autonomous quadrocopters are fundamentally different in their dynamic behavior from other existing musical robots. To prove the feasibility of the project, we must therefore ask: Is it possible to precisely time a rhythmic quadrocopter movement with a music beat? In the following, a simple motion primitive is selected which highlights the quadrocopter's characteristic properties and for which a solution to the synchronization problem is sketched. The details of the synchronization algorithm are found in [43].

A. A Side-To-Side Motion

A planar side-to-side motion as depicted in Fig. 3 is considered, where at beat times the vehicle reaches the outermost points of the trajectory. Given the music frequency f_d (obtained from an a priori music analysis), a corresponding desired sinusoidal vehicle trajectory can be defined in the $xz-$plane,

$$\begin{aligned} x_d(t) &= A_d \cos(\omega_d t) \\ z_d(t) &= z_d = \text{constant}, \end{aligned} \tag{1}$$

with $\omega_d = 2\pi f_d$ assumed to be constant. Fig. 4 illustrates the beat-motion relation. The altitude of the quadrocopter is stabilized at a given height z_d.

B. The Quadrocopter Dynamics

The side-to-side motion (1) is defined in the $xz-$plane. In-plane and out-of-plane dynamics are thus decoupled. Additional degrees of freedom are separately stabilized and do not affect the rhythmic motion. The equations governing

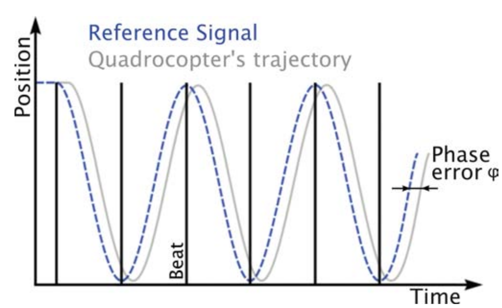

Fig. 4. Reference trajectory in lateral direction (dashed line) with corresponding quadrocopter motion (solid line). Vertical lines represent beat times.

the dynamics of the system are then given by

$$\ddot{z}(t) = f(t)\cos\theta(t) - g \tag{2}$$
$$\ddot{x}(t) = f(t)\sin\theta(t) \tag{3}$$
$$\dot{\theta}(t) = u(t), \tag{4}$$

where g is the gravitational constant and $\theta(t)$ is the pitch angle, see Fig. 3. The inputs to the system are the normalized thrust $f(t)$ in m/s^2 and the pitch rate $u(t)$ in rad/s.

C. Control and Synchronization

Underlying controllers turn the unstable quadrocopter dynamics into an oscillating system. A phase comparator detects the phase error between the desired reference trajectory and the actual quadrocopter motion. After having determined the phase error, it is compensated for by closing the loop, similar to [16] and [26].

The oscillating quadrocopter motion is achieved by using a cascading controller: the z-direction is stabilized first and, assuming a constant height, the trajectory-tracking controller for the x-direction is then designed. With

$$f(t) = \frac{1}{\cos\theta(t)}\Big(g - 2\delta_z\omega_z\,\dot{z}(t) - \omega_z^2\,(z(t) - z_d)\Big), \tag{5}$$

and an appropriate choice of the parameter δ_z and ω_z, the dynamics in z-direction are stabilized, cf. [43]. Building upon the above control scheme (5) and assuming a resulting constant height z_d, the thrust $f(t)$ is

$$f(t) = \frac{g}{\cos\theta(t)}. \tag{6}$$

With (6), to first order, the x-dynamics (3) reduce to

$$\ddot{x}(t) = g\,\theta(t) \quad \Leftrightarrow \quad \dddot{x}(t) = g\,u(t), \tag{7}$$

assuming small $\theta(t)$. With the aim of following the desired sinusoidal side-to-side motion (1), the input

$$u(t) = \frac{1}{g}\left(\overline{u}_1(t) + \overline{u}_2(t)\right) \tag{8}$$

is composed of a feedforward component,

$$\overline{u}_1(t) = \dddot{x}_d(t) = A_d\omega_d^3\sin(\omega_d t), \tag{9}$$

and an additional feedback term to correct for errors,

$$\overline{u}_2(t) = \alpha\,\left(\ddot{x}_d(t) - \ddot{x}(t)\right) + \beta\,\left(\dot{x}_d(t) - \dot{x}(t)\right) + \gamma\,\left(x_d(t) - x(t)\right), \tag{10}$$

with the tuning parameters α, β, and γ. When applying the input $u(t)$ as defined in (8), a phase shift is observed between the reference trajectory of the sideways motion and the actual quadrocopter trajectory, illustrated in Fig. 4. (Corresponding experimental results are shown in Fig. 5.) This phenomenon results mainly from unmodeled dynamics which were neglected in the controller design, such as communication delays and propeller dynamics. This problem is resolved in two stages. First, the phase shift $\varphi(t)$ between the quadrocopter trajectory $x(t)$ and the desired motion (1) is determined by an integration over a full period $T_d = \frac{1}{f_d}$,

$$\eta_1(t) = \frac{1}{T_d}\int_{t-T_d}^{t} x(t)\cos\left(\omega_d t\right)\,dt = \frac{A}{2}\cos\varphi_t \tag{11}$$
$$\eta_2(t) = \frac{1}{T_d}\int_{t-T_d}^{t} x(t)\sin\left(\omega_d t\right)\,dt = -\frac{A}{2}\sin\varphi_t, \tag{12}$$

where

$$\varphi_t = -\arctan\left(\frac{\eta_2(t)}{\eta_1(t)}\right). \tag{13}$$

In stage two, the phase error φ_t is corrected by a feedback technique borrowed from PLL design [44] shifting the reference signal $x_d(t)$ in (1) by a correction term $e(t)$,

$$x_d^s(t) = A_d\,\cos\big(\omega_d t + e(t)\big),\ \text{with}\ e(t) = -k\int_0^t \varphi_t\,dt. \tag{14}$$

Similarly, the derivatives of $x_d(t)$ in (8) are shifted in phase by $e(t)$. With the feedback integrator term $e(t)$, precise and robust phase locking is achieved. Convergence behavior is controlled by tuning the gain factor k.

Experimental results support the theoretical idea, see Fig. 5 and 6. Without phase correction a constant, non-zero phase error remains, while with the proposed phase correction method, the phase error converges to zero and perfect synchronization is achieved. Note that even when the phase error between the reference trajectory and the actual quadrocopter response is hardly noticeable in Fig. 5, actual experiments show that small phase errors remain visible and audible to humans.

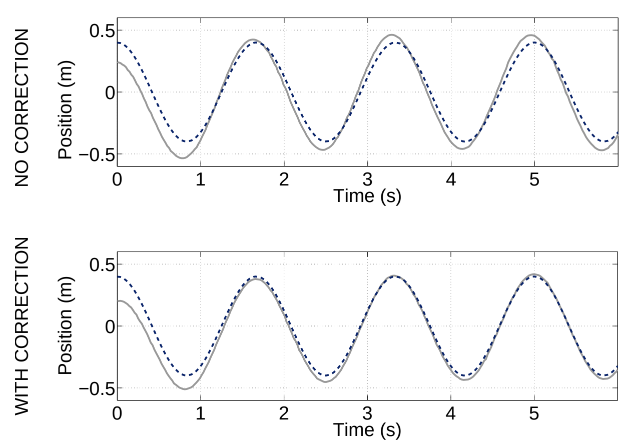

Fig. 5. Quadrocopter response to the dashed-lined input signal for the case of no phase correction (top) and phase error compensation (bottom). The solid line represents the vehicle trajectory.

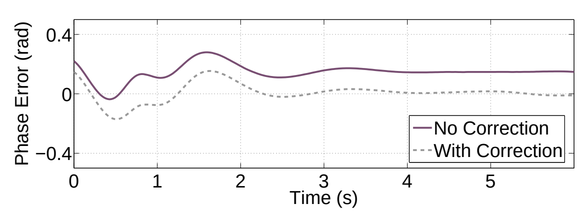

Fig. 6. Phase error of the vehicle trajectories shown in Fig. 5 (detected by the phase comparator).

IV. A Dance Performance

In the previous section, the fundamental basis of the work was presented: a quadrocopter motion that is synchronized to music. This is the first successful step towards choreographing a flying music show. Below, the overall concept and vision is outlined together with the corresponding steps necessary to realize this idea.

A. Vision

We envision the Flying Machine Arena as a stage for a dance performance featuring multiple quadrocopters, which move in rhythm to music and perform flips, eights, circles and other aggressive maneuvers. Our goal is to be able to quickly process any arbitrary piece of music and translate it into choreography that reflects the music's character.

To this end, the development of the musical platform can be divided into four main components: music analysis, motion design, vehicle control, and, finally, motion choreography. The different steps are illustrated in Fig. 7 and discussed next.

B. Music Analysis

Humans often tap their feet to the beat of music as a reflection of their rhythmic perception. Music comprehension is not based solely on rhythm, however. Humans are able to perceive a sophisticated ensemble of musical features - including melody, measure, pitch, dynamic range and recurring themes - which help them to associate emotions with what they are listening to, and to react with a corresponding range of emotive movements we refer to as 'dance'.

Thus far, robotic perception of music has been largely limited to beat tracking. Early beat tracking algorithms were developed as early as 1994 [45], and automated beat tracking is still an active area of research. Recent work includes [30], [31], [34]–[36]. Given the current state of the art, can we expect robots to perceive and respond to music in a manner sophisticated enough to call 'dance'? Which music features are responsible for human musical perception? Is it possible to extract these features from the music and correlate them with emotional expression?

A multiscale music analysis is fundamental to the creation of a meaningful choreography. The music is digitized and divided into different sections that are categorized according to rhythm, melody and character. The result is a vocabulary that describes the temporal development of the music, which is in turn coupled with a variety of quadrocopter movements.

The proposed application aims to automate and accelerate this process. For now, however, a semi-assisted system is a reasonable expectation: Software processes a piece of music and suggests a categorization to a human user, who oversees and corrects the results. This information is then forwarded to the choreography component, which will create a suitable composition of motions for the quadrocopters, see Section IV-E.

C. Motion Design

As already mentioned in Section I, defining suitable rhythmic motion primitives for quadrocopters is a major challenge. When developing a dancing performance, two different types of motion are distinguished:

Synchronized Motion – Movements that aim to follow the rhythm of the music must be precisely synchronized to the beat (or multiple of it). Normally, these are swing motions, consisting of sinusoids – which enable the ready measurement and correction of phase error – to achieve perfect synchronization. The side-to-side motion described in Section III belongs to this type of motion primitives.

Triggered Motion – Movements that are not strictly linked to the rhythm of the music, but start at a beat time, are executed during a given time interval, and end again with a music beat. These motion primitives are used to transition between two different synchronized motions, or to reflect a particular section of the music. Aggressive trajectories, like flips, eights, and circles, belong to this group of motion primitives.

Numerous motions can be created and cataloged according to the above categories. In this way, a library of motion primitives is built, serving as an important resource for the creation of new choreographies.

D. Vehicle Control

As emphasized in Section I, sophisticated methods are required in order to control a quadrocopter's dynamics.

The synchronized and triggered motions introduced above have to be carried over into the real world, and different control challenges are associated with each. Triggered motions are complex and highly dynamic maneuvers requiring fast controllers and appropriate feedforward terms, which may need to be acquired through (machine) learning. In contrast, synchronized motions are less aggressive and easier to follow, but require special attention to maintain precise timing.

According to [46], two notes are perceived as being simultaneous if they occur within less than 30 ms. Accuracy with respect to beat times must therefore be in this range, too. To define and measure the timing error, we introduced the concept of phase in Section III. Indeed, the music beat can be translated into a sinusoidal signal which builds the reference trajectory for the synchronized motion. In this case, a timing error is reflected by a non-zero phase error between the music reference and the actual vehicle trajectory. If trajectories are representable by a sinusoidal, phase-dependent description (as e.g. eights or circles), the timing error can always be obtained from the phase error. After having recognized the phase error, an approach like the one described in Section III can be used to compensate for it, achieving a precisely synchronized motion.

E. Motion Choreography

The previous steps result in a categorized piece of music (from the music analysis, see Section IV-B) and a library of motion primitives (from the motion design, see Section

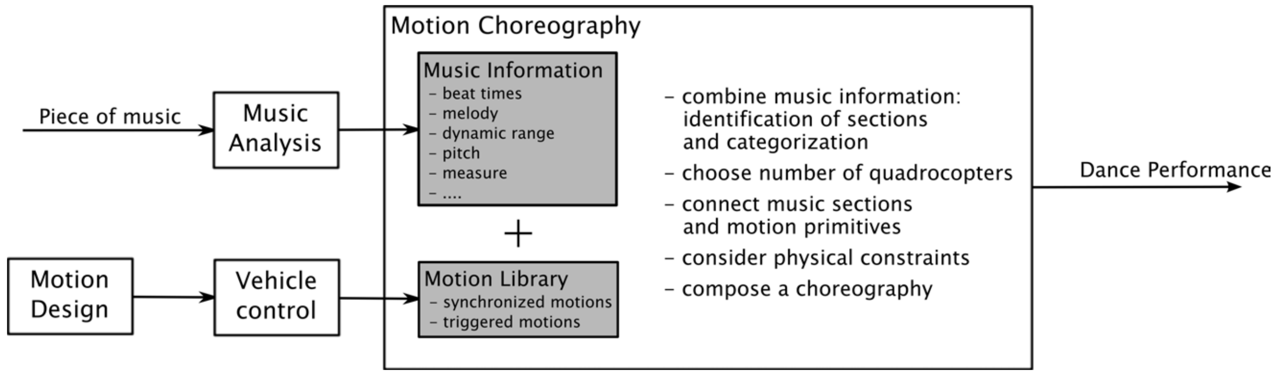

Fig. 7. The proposed platform: combining music and quadrocopter motion into a multi-vehicle dance performance.

IV-C). The physical limits of the vehicles and the space are already known. Is it possible to combine all this information in a meaningful way? How can multiple quadrocopters fly in a manner we can recognize as 'dance'?

Well-established and recognizable parameters for human dance have long been in use by professional dancers, choreographers and dance teachers to build choreography with interest, dynamics and aesthetic appeal. These parameters can provide us with a framework for meaningful quadrocoptor choreography, and are described as follows:

Space – Space refers to the area the dancer is performing in and also relates to how the dancer moves through the area as characterized by the direction and path of a movement, its size, level, and shape.

Time – Time encompasses rhythm, tempo, duration, and phrasing of movements. Using time in different combinations to music can create intricate visual effects. Ideas such as quick-quick, slow or stop movements are examples.

Energy – Energy relates to the quality of movement. This concept is recognizable when comparing ballet and tap dance. Some types of choreography are soft and smooth, while others are sharp and energetic.

Structure – Structure represents the organization of movement sequences into larger concepts: the combination and variation of movements using recurring elements, contrast, and repetition. Movements can even follow a specific story line to convey specific information through a dance.

With these parameters in mind, the motion primitives described in Section IV-C can eventually be combined into sequences, which can in turn be combined to create an overall choreographic performance. Endless permutations are possible, much the way individual words can be combined into a variety of subtle and sophisticated stories. Finally, an expressive connection of music sequences and motion primitives is established capable of visually conveying the music's emotions to the audience. As choreographing performances for human dancers, creativity and aesthetic judgment is required to achieve artistic quality.

V. CURRENT STATUS

So far, our research has been primarily focused on control and synchronization. As explained in Section III, a method was developed that is able to precisely synchronize a sinusoidal quadrocopter motion to a given music reference signal. Currently, a horizontal swing motion in the xz-plane and a similar motion in the yz-plane are implemented using the proposed algorithm. This allows a dancing behavior both along the x- and y-axis. Using multiple vehicles, this already leads to a wide range of combinations and patterns.

In addition to synchronized motions, aggressive trajectories are flown in the FMA with high accuracy and an impressive smoothness. Our research group is pushing the limits of what can be achieved with quadrocopters. For example, the quadrocopters learned to perform up to three flips, cf. [39].

A variety of motion primitives are now available in our library, discussed in Section IV-C. More complex motions of both types will be investigated in order to add variation to our quadrocopter dance performances. As mentioned in Section I, the motion design is not trivial and requires further research. Specifically, a transition motion capable of taking the quadrocopters from the final position of one rhythmic motion primitive to the starting position of the following motion must be implemented. The transition motion should be fast and guarantee a collision-free position change.

We developed a software platform built on a collection of synchronized motion primitives to guide the choreography of multiple quadrocopters flying together. A graphical user interface (GUI) allows the user to assign desired motions to specific quadrocopters, set all the necessary parameters, take off and fly the vehicles. This platform is especially important for testing new motions. The results shown in Section V-A were developed using this software platform. The dance motion presented in Section V-B is also incorporated into the graphical interface. The platform is connected to a simulation environment that is part of the FMA's infrastructure, see Section II. The simulation environment provides a 3D view of the FMA and allows to visually determine the quality of a new motion or controller. As new motion primitives are created, they can be immediately added to the software platform.

In order to create a dancing performance, as in Section V-B, the beat times have to be extracted from the music. This process was done with the aid of Beatroot [31]. Beatroot

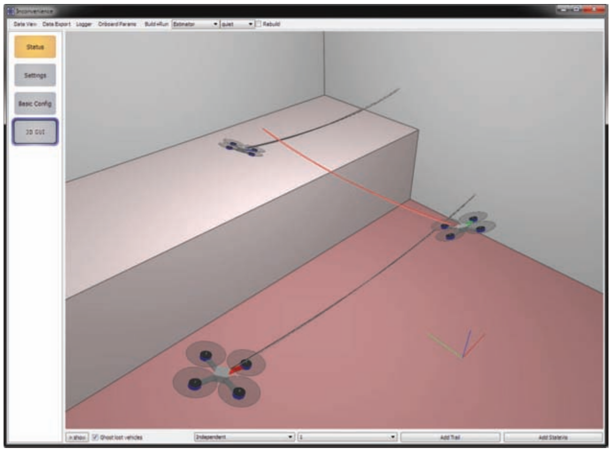

Fig. 8. A three-vehicle swing motion synchronized to the music beat; screen shot of our simulation environment.

analyzes the music and provides beat times. An interface visualizes the beats, such that the user can listen to the music and adjust the beat times if mismatches are noticed.

For designing the dance choreography, the extracted beat times give the underlying frequency. The performance combines the synchronized motions and the triggered motions. After having analyzed a piece of music, the setup of a new dancing performance is simple and can be done in short time; however, this procedure is not yet automated. The assignment of different motions to different sections of the music is done manually in order to reflect the character of the musical piece. In an interdisciplinary exchange, we hope to learn more about methods that are able to perform the multiscale analysis, as discussed in Section IV-B, and identify the different parts of a musical piece.

Most of our work has focused on the control of the quadrocopters and their motions. We are still looking for an automated method to retrieve information from music. Given this information, the key challenge will be to develop an algorithm for automatic choreography and motion planning. The results presented in this paper show the first steps towards a musical platform as presented in Section IV.

The two examples presented below show the capabilities of the current platform.

A. Example: Three-Vehicle Swing Motion

One possibility offered by the platform is to manually assign synchronized motions to specific quadrocopters. This can be done for testing purposes or simply to produce variation in the performance. The example demonstrates how the platform integrates multiple quadrocopters executing different motions: two vehicles perform a swing motion in the x-direction, while another one crosses their trajectories with a swing motion in the y-direction, see Fig. 8. Using the methods developed in [43], synchronization is achieved between the motion of the three quadrocopters and the music beat. The method is robust to the differences between the vehicles (e.g. due to the marker's position on the vehicle). The experimental results are shown in the attached video `http://tinyurl.com/DancePlatform`.

B. Example: Dancing Performance with Two Vehicles

We also developed a dancing performance for two vehicles based on a remix of the 'Pirates of the Caribbean' sound track. First the music is analyzed and the beat times are extracted. Then the different parts of the musical piece are identified and manually assigned to suitable motions from the library. In this example, a circle trajectory is chosen while the quadrocopters spin. Combinations with different speed and circle radii are shown in the associated video `http://tinyurl.com/DancePlatform`. The dancing parts consist of the swing motion presented in Section III. The amplitude is varied to achieve different effects.

VI. Conclusion

In this paper, a novel musical experience is proposed: flying vehicles that express the character of the music by performing an aerial dance. A cubic indoor flight space forms the stage, and small autonomous quadrocopters are the actors of this performance. Current features of the platform include the control of the quadrocopters and an audio-motion synchronization. A software infrastructure is built to be easily extendible with regard to the future objectives. One prospective feature is an automated multiscale music analysis that is able to identify distinct musical characteristics including beat, measure, dynamic range, melody and recurring themes. Building upon this information, the project aims towards an automated generation of coordinated musical multi-vehicle movements.

This project lies at the interface between robotics, control and music information retrieval, and has thus far been focused on the control aspect. The project's interdisciplinary nature requires intensive exchange and close cooperation with researcher in other fields. To this end, we are able to provide the experimental setup and control knowledge; we seek input concerning musical information retrieval and interpretation of music features.

VII. Acknowledgements

This work would have not been possible without the prior work of Markus Hehn and Sergei Lupashin. Their contributions are gratefully acknowledged.

References

[1] E. Singer, J. Feddersen, C. Redmon, and B. Bowen, "LEMUR's musical robots," in *Proceedings of the Conference on New Interfaces for Musical Expression (NIME)*, 2004, pp. 181–184.

[2] R. B. Dannenberg, B. Brown, G. Zeglin, and R. Lupish, "McBlare: a robotic bagpipe player," in *Proceedings of the International Conference on New Interface for Musical Expression (NIME)*, 2005, pp. 80–84.

[3] A. Kapur, "A history of robotic musical instruments," in *Proceedings of the International Computer Music Conference*, 2005, pp. 21–28.

[4] N. A. Baginsky, "The three sirens: a self-learning robotic rock band," Available online at www.the-three-sirens.info (accessed June 23, 2010), 2004.

[5] G. Weinberg, S. Driscoll, and M. Parry, "Musical interactions with a perceptual robotic percussionist," in *Proceedings of the IEEE International Workshop on Robot and Human Interactive Communication (ROMAN)*, 2005, pp. 456–461.

[6] G. Weinberg and S. Driscoll, "The design of a perceptual and improvisational robotic marimba player," in *Proceedings of the IEEE International Symposium on Robot and Human Interactive Communication (ROMAN)*, 2007, pp. 769–774.

[7] G. Hoffman and G. Weinberg, "Gesture-based human-robot jazz improvisation," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*, 2010, pp. 582–587.

[8] J.-J. Aucouturier, "Cheek to chip: dancing robots and AI's future," *IEEE Intelligent Systems*, vol. 23, no. 2, pp. 74–84, 2008.

[9] K. Shinozaki, A. Iwatani, and R. Nakatsu, "Construction and evaluation of a robot dance system," in *Proceedings of the IEEE International Symposium on Robot and Human Interactive Communication (ROMAN)*, 2008, pp. 366–370.

[10] D. Grunberg, R. Ellenberg, Y. Kim, and P. Oh, "Creating an autonomous dancing robot," in *Proceedings of the International Conference on Hybrid Information Technology (ICHIT)*, 2009, pp. 221–227.

[11] A. Nakazawa, S. Nakaoka, K. Ikeuchi, and K. Yokoi, "Imitating human dance motions through motion structure analysis," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2002, pp. 2539–2544.

[12] J. Oliveira, F. Gouyon, and L. P. Reis, "Towards an interactive framework for robot dancing applications," in *Proceedings of the International Conference on Digital Arts (ARTECH)*, 2008.

[13] K. Kosuge, T. Hayashi, Y. Hirata, and R. Tobiyama, "Dance partner robot – Ms DanceR," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, vol. 4, 2003, pp. 3459–3464.

[14] S. Kotosaka and S. Schaal, "Synchronized robot drumming by neural oscillator," *Journal of the Robotics Society of Japan*, vol. 19, pp. 116–123, 2001.

[15] K. Murata, K. Nakadai, K. Yoshii, R. Takeda, T. Torii, H. G. Okuno, Y. Hasegawa, and H. Tsujino, "A robot uses its own microphone to synchronize its steps to musical beats while scatting and singing," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2008, pp. 2459–2464.

[16] K. Yoshii, K. Nakadai, T. Torii, Y. Hasegawa, H. Tsujino, K. Komatani, T. Ogata, and H. G. Okuno, "A biped robot that keeps steps in time with musical beats while listening to music with its own ears," in *Proceediings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2007, pp. 1743–1750.

[17] R. Takeda, K. Yoshii, K. Komatani, T. Ogata, and H. G. Okuno, "A robot listens to music and counts its beats aloud by separating music from counting voice," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2008, pp. 1538–1543.

[18] F. Thorn, "Felix's machines," Available online at www.felixsmachines.com (accessed June 22, 2010), 2008.

[19] C. Southworth and L. Hasan, "Ensemble robot," Available online at www.ensemblerobot.com (accessed June 22, 2010), 2004-2006.

[20] K. Murata, K. Nakadai, K. Yoshii, R. Takeda, T. Torii, H. G. Okuno, Y. Hasegawa, and H. Tsujino, "A robot singer with music recognition based on real-time beat tracking," in *Proceedings of the 9th International Conference on Music Information Retrieval (ISMIR)*, 2008, pp. 199–204.

[21] K. Murata, K. Nakadai, R. Takeda, H. G. Okuno, T. Torii, Y. Hasegawa, and H. Tsujino, "A beat-tracking robot for human-robot interaction and its evaluation," in *Proceedings of the IEEE/RAS International Conference on Humanoid Robots*, 2008, pp. 79–84.

[22] M. P. Michalowski, S. Sabanovic, and H. Kozima, "A dancing robot for rhythmic social interaction," in *Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, 2007, pp. 89–96.

[23] C. Crick, M. Munz, and B. Scassellati, "Synchronization in social tasks: robotic drumming," in *Proceedings of the IEEE International Symposium on Robot and Human Interactive Communication (ROMAN)*, 2006, pp. 97–102.

[24] G. M. Hoffmann, H. Huang, S. L. Wasl, and C. J. Tomlin, "Quadrotor helicopter flight dynamics and control: theory and experiment," in *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, 2007.

[25] T. Takeda, K. Kosuge, and Y. Hirata, "HMM-based dance step estimation for dance partner robot – Ms DanceR," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2005, pp. 3245–3250.

[26] D. Pongas, A. Billard, and S. Schaal, "Rapid synchronization and accurate phase-locking of rhythmic motor primitives," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2005, pp. 2911–2916.

[27] K.-M. Chen, S.-T. Shen, and S. D. Prior, "Using music and motion analysis to construct 3D animations and visualisations," *Digital Creativity*, vol. 19, no. 2, pp. 91–104, 2008.

[28] K. Takahashi and H. Ueda, "A dance synthesis system using motion capture data," *Knowledge Acquisition: Approaches, Algorithms and Applications*, pp. 208–217, 2009.

[29] F. Ofli, E. Erzin, Y. Yemez, and A. M. Tekalp, "Multi-modal analysis of dance performances for music-driven choreography synthesis," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, 2010.

[30] G. Tzanetakis, "Marsyas: music analysis, retrieval and synthesis for audio signals," Available online at www.marsyas.info (accessed June 26, 2010), 2009.

[31] S. Dixon, "Beatroot: an interactive beat tracking and visualisation system," Available online at www.elec.qmul.ac.uk/people/simond/beatroot/ (accessed June 26, 2010), 2006.

[32] M. S. Puckette, T. Apel, and D. D. Zicarelli, "Real-time audio analysis tools for Pd and MSP," in *Proceedings of the International Computer Music Conference*, 1998, pp. 109–112.

[33] M. Goto, "An audio-based real-time beat tracking system for music with or without drum-sounds," *Journal of New Music Research*, vol. 30, no. 2, pp. 159–171, 2001.

[34] M. F. McKinney, D. Moelants, M. E. P. Davies, and A. Klapuri, "Evaluation of audio beat tracking and music tempo extraction algorithms," *Journal of New Music Research*, vol. 36, no. 1, pp. 1–16, 2007.

[35] D. P. W. Ellis, "Beat tracking by dynamic programming," *Journal of New Music Research*, vol. 36, no. 1, pp. 51–60, 2007.

[36] Y. Shiu and C.-C. J. Kuo, "Musical beat tracking via Kalman filtering and noisy measurements selection," in *Proceedings of the IEEE International Symposium on Circuits and Systems (ISCAS)*, 2008, pp. 3250–3253.

[37] Ascending Technologies GmbH, "Multi-rotor air vehicles," Available online at www.asctec.de (accessed June 27, 2010), 2010.

[38] D. Gurdan, J. Stumpf, M. Achtelik, K.-M. Doth, G. Hirzinger, and D. Rus, "Energy-efficient autonomous four-rotor flying robot controlled at 1 kHz," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*, 2007, pp. 361–366.

[39] S. Lupashin, A. Schöllig, M. Sherback, and R. D'Andrea, "A simple learning strategy for high-speed quadrocopter multi-flips," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*, 2010, pp. 1642–1648.

[40] Vicon, "Motion capture systems," Available online at www.vicon.com (accessed June 27, 2010), 2010.

[41] J. P. How, B. Bethke, A. Frank, D. Dale, and J. Vian, "Real-time indoor autonomous vehicle test environment," *IEEE Control Systems Magazine*, vol. 28, no. 2, pp. 51–64, 2008.

[42] G. Ducard and R. D'Andrea, "Autonomous quadrotor flight using a vision system and accommodating frames misalignment," in *Proceedings of the IEEE International Symposium on Industrial Embedded Systems (SIES)*, 2009, pp. 261–264.

[43] A. Schöllig, F. Augugliaro, S. Lupashin, and R. D'Andrea, "Synchronizing the motion of a quadrocopter to music," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*, 2010, pp. 3355–3360.

[44] W. F. Egan, *Phase-Lock Basics*, 2nd ed. Wiley-Interscience, 2008.

[45] M. Goto and Y. Muraoka, "A beat tracking system for acoustic signals of music," in *Proceedings of the ACM International Conference on Multimedia*, 1994, pp. 365–372.

[46] R. Rasch, "The perception of simultaneous notes such as in polyphonic music," *Acustica*, vol. 40, no. 1, pp. 21–33, 1978.