Towards Modeling Song Propagation in Humpback Whales Using Multi-Agent Systems for Musical Composition

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Abstract
We present a multi-agent system which incorporates mobile agents that communicate using a simple song-grammar made up of a small vocabulary. Agents are attracted to move towards other agents who by singing demonstrate a similar grammar. Agents also adapt their grammars based on the singing of other nearby agents. The closer the nearby agents are, the greater the influence. These features consistent with a number of the proposed hypotheses for the singing behaviours of Humpback whales and other marine mammals. As a result of these features we show how over time the agents song grammars become more correlated, and agents which are closer geographically have more closely correlated grammars. Furthermore the agents group into clusters, or "schools", which exhibit highly correlated grammars, and hence similar songs, and will tend to continue moving in these "schools".

Keywords: multi-agent systems, algorithmic composition, multi-agent modeling, humpback whale, artificial life, whale song

1. Multi-agent music
Multi-agent models have also been widely employed in fields such as evolution and ecology (Grimm and Railsback 2005). One of the first was "boids" (Reynolds 1987), which simulated animal flocking, herding and schooling. More recent have been multi-agent models of a lake aquatic eco-system (Lia et al. 2010), and earthworms (Blanchart etl al. 2009). Multi-agent models are a useful tool for studying processes too complex to be satisfactorily captured by analytical approaches. Other examples of this approach include a model of cooperative foraging in bottle-nosed dolphins, which has been used to develop methods for coalition formation in multi-agent systems (Haque and Egerstedt 2009) and modeling whale watching tours (Anwar 2007).

Multi-agent modelling has been used in investigating the emergence of musical culture. In Miranda's (Miranda et al. 2010) agents can selectively imitate each others' performances depending on their musical preferences, giving a form of evolutionary algorithm that closely mimics the kind of social learning processes in animals, widely studied by Rendell (Rendell et al. 2011). As a result of the social bonding interactions a community repertoire begins to emerge. (Gong et al. 2005) produced a simple music composing system investigating the emergence of musical culture. It was found that in the emergent social network the agents tended to create clusters of preference factors according to their musical preferences.

These multi-agent musical culture techniques have been the inspiration for a number of computer-aided composition and performance systems. Kirke utilizes simple models in which agents sing to each other and concatenate their songs (Kirke and Miranda 2008). Kirke and Miranda follow a similar approach but when agents sing to each other, they change their musical range and pitch centre based on what they hear from other agents (Kirke and Miranda 2011). In (Kirke 2012) agents each have their own internal states representing motivation or emotion and adjust their songs based on this. Furthermore an agent adjusts its internal states based on the songs it hears and concatenates from other agents.

2. Cetacean communication

The vocal behaviour of cetaceans is a fast expanding current research area worldwide (e.g. (Yurk et al. 2002)(Noad et al. 2000)(Rendell and Whitehead 2003) to cite only 3 out of many). This interest is largely explained by the highly complex vocal behaviour of cetaceans, including vocal learning, vocal signatures and vocal dialects. This proposal focuses on the singing behaviour of Humpback whales. On winter breeding grounds male Humpback whales produce hierarchically structured songs with repeated complex themes, cycling completely with a periods between 5-25min (Payne and McVay 1971). The precise function of the singing behaviour is a matter of ongoing debate. At any time, all males in a breeding population sing nearly the same song, but the song evolves structurally over time, changing noticeably over a breeding season, substantially over periods of several years, but remaining stable over the largely non-singing summer months (Payne and Payne 1985). Males sing virtually identical songs on breeding grounds thousands of kilometres apart, and the songs on these different grounds evolve as one. For instance, songs from Maui, Hawaii and Islas Revillagigedo, Mexico (4,500km apart) are similar at any time but change in the same way over a two-year period (Payne and Guinee 1983). For this to happen, there must be some level of interaction between singers in order for changes in song to be spread across populations. Scientists hypothesize that singing may aid grouping in populations (Darling et al., 2006).

The songs have been analyzed manually over the years but there has not been an automated extensive grammar analysis. An automated method was proposed in (Walker and Fisher 1997) but as far as we are aware was never investigated, and it was not based explicitly in developing multi-agent methodologies. Like most language and western music, Humpback whale song has a hierarchical structure. The lowest level elements are basic units. These are organized into sets of units called phrases. A phrase usually consists of a unit pair, for example a pitch and a percussive sound, each repeated a number of times. The phrases are combined into sequences of one or more similar phrases, called themes. These themes can consist of one of several patterns of phrases. For example phrases that change very little, or phrases whose content slowly moves from one type of unit to another. Groups of, usually, four to ten themes arranged in a relatively fixed ordering combine to make up the final song. Humpback whales repeat the song dominating their current population in song sessions lasting, often, for many hours. Some Humpback whale song units, which have been derived by (Walker et al. 1996)(Picot et al. 2008). Picot and collaborators determined 6 different patterns of Humpback song intonation through automatic segmentation of Humpback whale recordings. Walker and collaborators present further methods for segmenting whale song automatically, and comparing the units for classification (though they do not perform an exhaustive classification).

3. Multi-agent model of humpback whale culture

A multi-agent system is now introduced – inspired by the authors' work in multi-agent music - which is proposed as a highly simplified model of humpback whale song and culture. Agents are located in a geographical two-dimensional space (a "sea"), and each agent has a song grammar, a song vocabulary, and the ability to move in the space ("swim"). All whales have the same vocabulary – these are abstract units (labelled "1", "2", "3", etc.) which substitute for the individual sound units generated by fundamental whale biology. This abstract non-sonic nature is not considered an issue at this early stage in the model development. Others have worked on Humpback whale unit synthesis algorithms, and the integration of these will be examined at a later stage.

A whale's location is represented by two numbers (x, y). The song grammar is a transitional grammar. Transitional probability is a feature used to identify patterns by humans (Seidenberg 1997). A whale's grammar is modelled as a simple 1-step Markov process. In this case each whale sound unit has a certain probability of being followed by another sound unit. So for example if the whale sings sound unit "1" then that whale's grammar will denote the probability of each of the other sound unit's occurring afterwards. The grammar is thus in the form of a 2-D Matrix. An example grammar is shown below for a whale with 5 vocabulary units.

0.04721	0.42405	0.11636	0.29206	0.12031
0.10727	0.16614	0.074008	0.2912	0.36138

0.16815	0.2302	0.19196	0.22466	0.18504
0.06909	0.30423	0.13002	0.29762	0.19905
0.10857	0.21881	0.18919	0.35496	0.12848

Row 1, Column 1 indicates the probability that after a whale has sung vocab-unit "1", it will sing it again (probability 0.047219, very low). The largest number if row 1 is in column 2 (0.42405). This indicates that the most probable utterance for this whale, after it has sung a "1", is to sing a "2". Note that all the probabilities in a row add up to 1, indicating that at least one of the utterances must follow. In this model, to generate a whale's song, an initial unit is chosen (usually unit "1" in the experiments in this paper). Then a random song is generated of a fixed length, based on the probabilities in the whale's grammar. So a whale will usually sing a slightly different song each time it sings, though it will always tend to sing in a certain way. The grammars can be designed to be much more tightly constrained than the above example. This corresponds to sparser matrices – leading to a whale singing only a small set of song variations.

4. Whale singing and influence

At each time step, when the model is running, a whale is randomly chosen from the population in the model. This whale will generate its song, as described above. This song will then be heard, with an intensity inversely proportional to the distance squared from the singing whale. So a whale 20 units away from the singer will hear the song with intensity factor 0.0025, whereas a whale 10 units away will hear the song with intensity factor 0.01. For larger distances in the real world whale song will obviously become inaudible. In this model the whale song is always audible if an agent is a finite distance from the singer, but become inaudible for all intents at purposes for large distances as it will have no influence on the distant whales.

The influence of the heard song is twofold:

1. Movement Influence
2. Grammar Influence

4.1 Movement influence

Whales all move by a small random amount at every time step. Furthermore, when a whale hears a song S it will move in the direction of that song, depending on how closely that song "fits in" with its own song (based on its grammar). So if a whale hears two whale songs equidistant to itself, it will tend to move towards the one which is most similar in structure to its own grammar. How does a whale compare a song to a grammar? This is done by generating what we call a "pseudo grammar" from the song. Suppose whale W1 hears the song S made up of the following units: "1", then "3", then "4" then "1" then "1". In the model W1 infers a pseudo grammar whose maximum likely transitions are from 1 to 3 and from 3 to 4, 4 to 1 and 1 to 1. Below is an example pseudo grammar matrix that conforms to this:

0.4717	0.018868	0.4717	0.018868	0.018868
0.2	0.2	0.2	0.2	0.2
0.034483	0.034483	0.034483	0.86207	0.034483
0.86207	0.034483	0.034483	0.034483	0.034483
0.2	0.2	0.2	0.2	0.2

This pseudo grammar is then compared to its own grammar by taking the Cartesian distance between the two. The more likely it is that whale W1's grammar could have produced song S, the more it will move towards the singing whale who sang S.

Obviously we are not suggesting that real humpback whales infer a grammar and perform a Cartesian distance (although European starlings can learn the statistical regularities within sound sequences constructed by an artificial grammar)(Berwick et al. 2011). However what we do know is that humpback whale song is non-deterministic, so it is desirable to have a statistical model rather than a fixed one. Furthermore, humpback whale song grammar is surprisingly complex and so it was desired to develop a sufficiently flexible model. This model allows for "almost-deterministic" sparse grammars to highly complex versions as well, and thus we feel it is a good first approximation to initiate further studies.

Movement influence is designed to cause whales which are likely to sing similarly structured songs will be close by.

4.2 Song influence

When a whale W1 hears a song S, it adjusts its own grammar based on the song it has heard, and how loudly it hears the song. This is done once against using the pseudo-grammar approach. W1 generates a pseudo grammar for S, and then takes a weighted average between its own grammar S. The weight is proportional to the cartesian distance from the singing whale. So if a whale is far away its song will have hardly any influence on W1, if it is close by its song will have quite a large influence on the grammar. If two whales have very similar grammars, they are more likely to sing similar songs (remember all whales have the same vocab units in this model).

Song influence is designed to cause whales which are close to by to be more likely to sing similarly structured songs.

5. Example implementations

We will now look at an implementation in which whales move through 5000 cycles of singing. In each cycle a whale is randomly picked (uniform random) to sing (i.e. to generate a song based on its grammar). In that same cycle each other whale has its grammar influenced by the song of that singing whale (based on how loudly it hears the song), and moves towards the singing whale with a speed based on how similar their grammars/songs seem to be.

In this experiment we will have 6 whales, in a sea size of 200 units. Each whale has a vocabulary of the same 5 utterance units: "1", "2", …, "5". When a whale's grammar is influenced by the song it is hearing that influence is halved to 50% using a parameter *influenceFactor*. When a whale moves towards another whale based on that song it hears, its movement is divided by 100 using a *movementInfluenceFactor* of 1%. These parameter settings were found by experiment, though other values are viable. On top of the movement caused by moving towards other whales songs, a whale moves randomly in a random direction in steps of size *2* x *movementInfluenceFactor*.

A series of 30 experiments were run. Across the 30 experiments the following was found:

- Whale grammars became more similar: the Cartesian distance between grammars shrunk by 54% on average
- Whales moved towards each other: The average distance between the 6 whales shrunk from 89 units to 42 units on average
- Whales that ended up closer together had more similar grammars: the correlation between whale closeness and the closeness of their grammars increased by 16% on average

Below are plots Figures 1, 2 and 3, from three separate experiments with the same parameter values as above. The small circles are the whales before the cycles are run, the large ones after 5000 cycles of interaction. They show how the whales are actually tending to cluster into subgroups or mini-"schools" in the "sea".

Figures 4, 5, 6 and 7 were generated using the same parameter values but for 24 whales, and over 20000 cycles. They show 4 stages respectively in whale behaviour in the same experiment. Also the random direction movements (i.e. those not influenced by singing) are made 10 times as large so as to make whale movements more visible. The whale positions are plotted every 6000 cycles of interaction. Looking at the four figures it can be seen that whales in the <W1,W6,W15,W20> "pod" in the top left hand corner moves downward together. The whales in the <W5,W9,W17,W23> pod in the bottom left corner move together. Similarly with the slower forming school in the bottom right hand corner: <W2,W10,W14,W19,W22>. Note because of the close distances kept over time, these whales in a pod with have much closer grammars. This closeness will lead to them moving towards each other, creating the geographical bonding cycle.

Figures 1, 2 & 3: Whale positions before and after 5000 cycles for three runs. Large circles are after the run

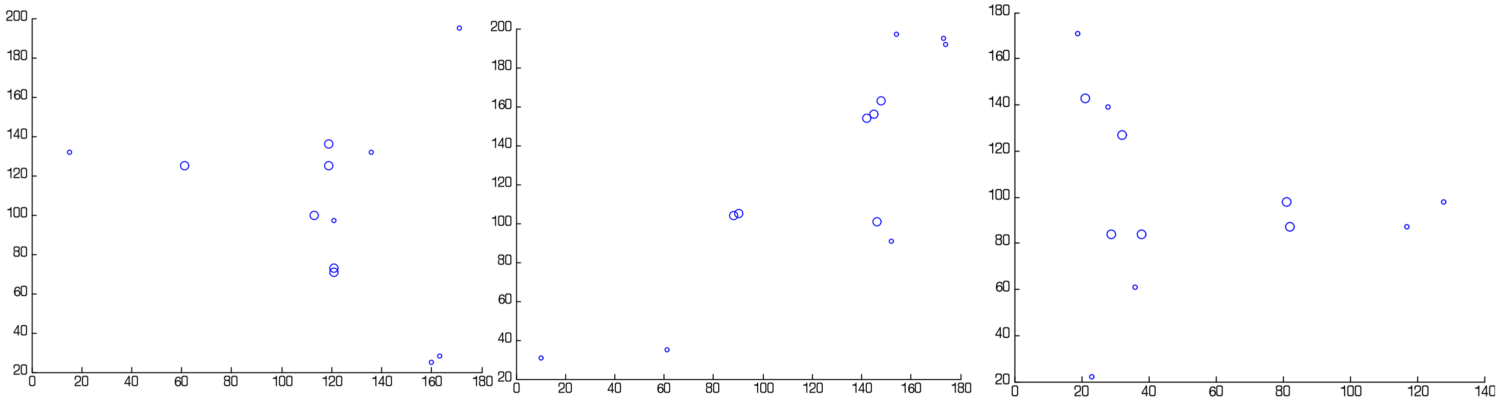


Figure 4: Whale schools moving together part 1

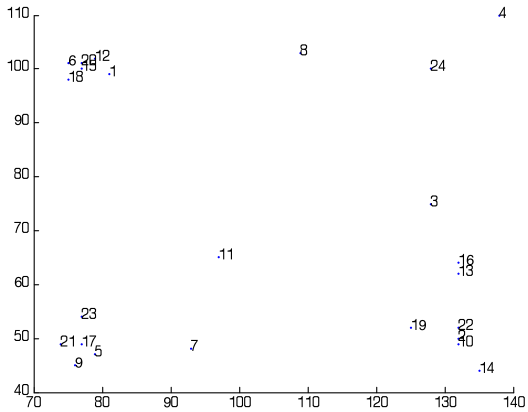
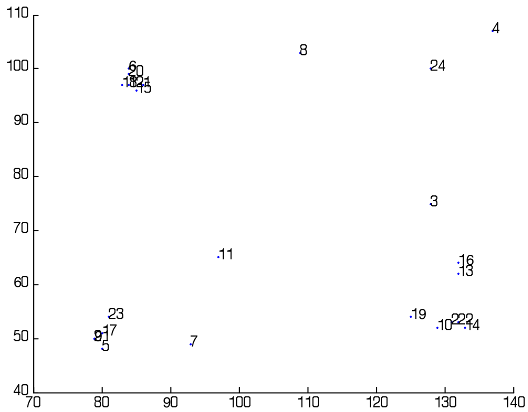


Figure 5: Whale schools moving together part 2



Figures 6: Whale schools moving together part 3

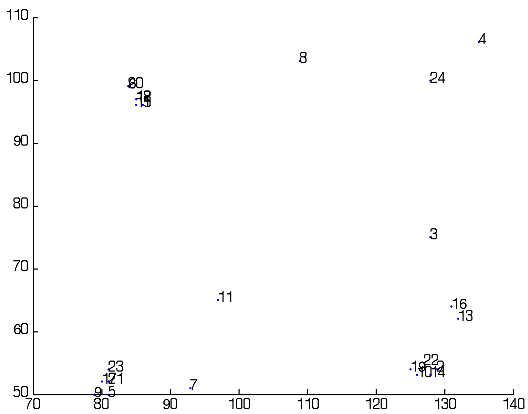
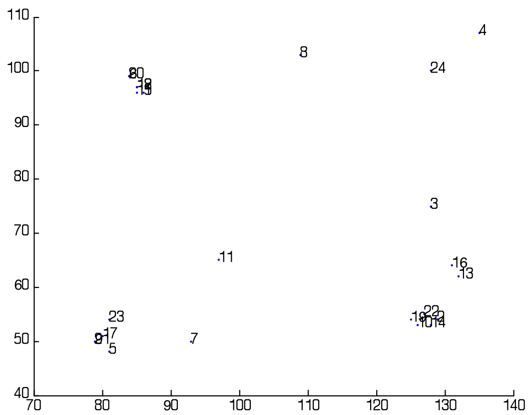


Figure 7: Whale schools moving together part 4



6. Conclusions and future work

In this paper it has been shown that a simplified model of humpback whale inspired by multi-agent music composition models, can be used to run experiments regarding simplified humpback interaction. As is found in real humpback whale pods, the model leads to the grammar of geographically close whales to being very similar. Furthermore it has been hypothesized by some biologists that whale song helps to bond whales in groups. The model demonstrates this hypothesis in action, where whales bond together into groups whose songs are similar, and then continue to move together.

In terms of future work the model needs to be extended to incorporate more features discussed in other hypotheses for humpback whale song purpose. Furthermore it needs to be extended to incorporate more elements known about humpback whale song. For example, real humpback whale songs are longer than the songs used in the current model, plus have more song unit types. Also modeling them as a first order markov model is unrealistic as true humpback whale song is shown to have a hierarchical musical structure which would require a higher order markov model.

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